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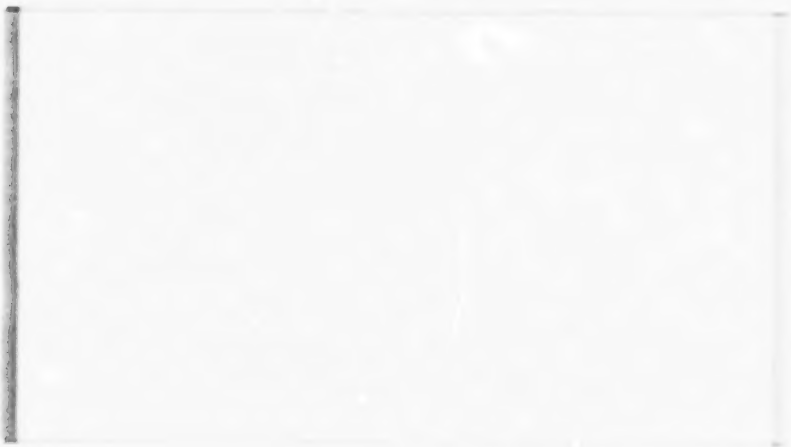

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STRESS ANALYSIS OF PRESSURE TUBE HYDRIDE BLISTERS PROGRESS REPORT (2)

Report No. 86-175-K

A.C. Wallace
Engineer
Nondestructive and Fracture Evaluation Section
Metallurgical Research Department

ABSTRACT

A series of finite element stress analyses have been performed to investigate the nature of the stresses resulting from the formation of zirconium hydride blisters in a pressure tube. Modifications were made to an existing model to more accurately describe the mechanical properties of the hydride phase and to include an analytical estimate of the hydrogen distribution within the blister. These refinements have resulted in stress and deformation estimates that are reasonably consistent with observations of actual blisters.

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EXECUTIVE SUMMARY

STRESS ANALYSIS OF PRESSURE TUBE HYDRIDE BLISTERS
PROGRESS REPORT (2)

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Nondestructive and Fracture Evaluation Section
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A series of finite element stress analyses have been performed to investigate the stresses associated with the formation of zirconium-hydride blisters on the outside surfaces of reactor pressure tubes. These stresses are a direct result of the 14-17% volume expansion which occurs during the transformation from the matrix to the hydride phase. Stresses due to internal pressurization or thermal gradients have not yet been considered.

The finite element model used in some earlier analyses was modified to permit yielding of the hydride phase in compression. This behaviour has been observed at temperatures greater than 100°C in studies of the deformation of pure zirconium hydrides and was also dependent on the hydrogen concentration. In addition, an improved estimate of the hydrogen distribution was incorporated into the model by transferring the results from a finite difference blister growth analysis onto the finite element mesh.

These modifications resulted in predictions of lower compressive stresses within the blister and improved predictions of blister protrusion. It was observed that as the hydrogen concentration within the blister was increased, the magnitude of the internal compressive stresses decreased. The stresses are relieved due to compressive yielding of the hydride phase which occurs at lower stresses for higher hydrogen concentrations. These results are also consistent with observations that the applied stress required to crack a blister decreases with increasing blister size.

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To Mr. D.W. Souther
Nuclear Systems Department
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STRESS ANALYSIS OF PRESSURE TUBE HYDRIDE BLISTERS PROGRESS REPORT (2)

1.0 INTRODUCTION

This report summarizes the most recent results in the program to determine the expansion stresses generated by the formation of a zirconium hydride blister in a pressure tube. The work reported here is a continuation of the work described in an earlier progress report/1/, which laid much of the groundwork for the present analysis.

The first progress report summarized a number of parametric case studies performed to determine the effects of variations in material properties and hydrogen distribution within the blister. Numerous other factors such as effects of spacing and aspect ratio were also investigated. While a great deal of useful information was obtained, some difficulties remained with the analysis.

The first of these was to accurately determine the material properties of the hydride phase. The stress-strain behaviour had been generally presumed to be linear elastic, with a lower elastic modulus than the surrounding matrix. This led to the prediction of unrealistically high compressive stresses within the blister, and stress discontinuities at the blister/matrix interface due to step changes in material properties at the interface.

The other problem with the earlier analysis lay in precisely determining the hydrogen disribution within the blister. This was shown in /1/ to have a considerable effect on the stress distribution since the amount of volume expansion at any point within the blister is dependent on the hydrogen concentration at that point.

Thus, the emphasis of the work described in this progress report was on improving the modelling of the material properties for the hydride phase and incorporating an accurate hydrogen distribution into the model.

2.0 METHOD OF ANALYSIS

2.1 Geometric Model and Finite Element Mesh Description

The two-dimensional axi-symmetric model used for the analysis was described in /1/. Basically, the blister is modelled to form on one surface of a flattened disc of pressure tube material. The origin of the axi-symmetric coordinate system, (r (radial), θ (circumferential) and z (vertical) directions), is defined from the outside (blistered) surface of the tube prior to blister formation, with the z direction corresponding to the axis of symmetry and being positive through the tube thickness. This is shown in Figure 1.

Two different finite element meshes were used for the analysis. They were basically similar, however, one was for the geometry of a Zircaloy-2 pressure tube while the other was for a Zr-2.5Nb tube. These meshes are shown in Figure 2. Both use 8-noded isoparametric axi-symmetric elements with a reduced integration scheme.

2.2 Modelling of Expansion

The formation of the zirconium hydride phase, which precipitates as platelets or needles when the hydrogen concentration exceeds the solubility limit, results in a volume increase in the range of 14-17%. The stresses due to this volume expansion are the main subject of these analyses. Stresses due to internal pressure or other factors such as thermal gradients were not investigated. The technique used was outlined in /1/, and basically relies on modelling volume expansion by means of a thermal expansion analogue, in which the hydrogen distribution within the blister is specified as a temperature distribution. The temperature corresponding to the delta zirconium hydride phase ($ZrH_{1.5}$,[H] = 16000 ppm or 60 atomic %) is arbitrarily set at T = 100 in the model. Similarly, T = 0 corresponds to the nominal hydrogen concentration in the matrix phase ([H] = 100 ppm or 0.9 atomic %). The normal expansion component at any point is then given by the product α T, where α is a linear expansion coefficient and T is a relative measure of the hydrogen concentration. Thus the variation in volume expansion throughout the blister was made proportional to the hydrogen distribution.

2.3 Overall Scope of Analysis

Basically two main analysis cases were considered. The first uses the Zircaloy-2 mesh of Figure 2.a and assumes a cosine distribution of the hydrogen concentration from the blister core to the interface. Initially, some time was spent determining the importance of the boundary conditions on the resultant stresses. The effects of anisotropic expansion were also briefly examined. Following this, efforts were concentrated on modifying the properties of the hydride phase to obtain more realistic results. The first step was to allow yielding of the hydride phase. The second step was to make both the elastic and post-yield response of the hydride phase proportional to the assumed hydrogen distribution.

The second main case utilized the Zr-2.5Nb mesh in Figure 2.b and used a hydrogen distribution interpolated from the results of a finite difference code developed for modelling blister growth. The material properties chosen for the hydride phase were those eventually developed in the previous case. Yielding of the hydride

phase was assumed and both elastic and elastic-plastic properties were made proportional to the hydrogen concentration. Finally, the effects of anisotropic volume expansion were again briefly examined.

3.0 ANALYSIS INVOLVING THE ZIRCALOY-2 MESH WITH A COSINE HYDROGEN DISTRIBUTION

The analysis described in this section uses Case A in Progress Report I/1/ as a starting point. The stress-strain behaviour in the hydride phase is assumed to be elastic with a value of the elastic modulus 30% lower than that of the matrix. The mesh shown in Figure 2.a was used.

3.1 Boundary Conditions

Some initial investigations were performed to determine whether or not the boundary conditions that had been applied to the mesh for previous analyses were really the most appropriate.

The Case A boundary conditions are shown in Figure 3. The axis of symmetry (left hand edge) was constrained to move in the vertical (z) direction only, except for the inside surface node which was fixed. The right hand edge of the mesh remained unconstrained, even though in reality it connects to adjacent tube material. Figure 4.a shows the displacement of this mesh after blister expansion corresponding to 1% linear strain. It can be seen that the blister acts like a jack and bends the specimen. This results in large tensile through-wall stresses beneath the blister which decay to zero or become slightly compressive near the tube inside surface (Figure 6).

In order to gauge the importance of the boundary conditions on the stresses, the analysis in Case A was repeated for the different conditions shown in Figure 3. For the first alternate case – referred to here as Case B, the boundary conditions were the same as in Case A except that the right hand edge of the mesh was also constrained to move only in the vertical (z) direction. Figure 4.b shows the displacement of the mesh after blister expansion corresponding to 1% linear strain. Although Figure 4 shows little apparent difference from Case A, the displacement of the right hand edge was reduced in Case B.

As a bounding case, the analysis in Case A was repeated again with both left and right hand edges rigidly constrained. This is Case C in Figure 3, and the resulting displaced mesh is illustrated in Figure 4.c. In this case, the displacements are evidently much less.

Finally, Case D in Figure 3 shows a mesh which attempted to better model the curved geometry of a pressure tube. In the axi-symmetric case this mesh represents the cap of a sphere as opposed to a flat disc. The boundary conditions restrict the motion of both edges to lie in radial planes extending from the centre of curvature of the mesh. This is similar to Case B except that it is not necessary to fix an additional node to prevent rigid body motions. Figure 4.d shows the displacements for this mesh after a 1% linear expansion of the blister. In this case, the largest displacements have occurred at the left hand side of the mesh instead of at the right, as in Cases A and B.

The through-wall and surface stresses at 1% linear expansions are compared for the four cases in Figures 5 and 6. It can be seen that the differences in the stresses for the different cases are negligible. Case C generally shows lower stresses, reflecting the higher constraint, but the stresses from cases A, B and D may be represented as a single line. It is possible that the differences may have become larger if the analyses were continued to the full 4% linear strain. However, these differences would still be small in relation to the uncertainty regarding the results. The main objective of the blister stress analysis project at this stage is to determine the main trends in the stress distributions associated with blister formation. It is not expected that the absolute stress values determined by the analysis will be accurate to more than about 10% and it would not be surprising if the accuracy was much worse. Thus the boundary conditions of Case A were applied in all subsequent analyses. This represents the least constrained case examined. In reality a blister in a pressure tube would experience greater constraint than this. However, these results indicate that the additional constraint is not expected to have a significant effect on the expansion stresses. The analysis of Case D also confirms that the effects of ignoring tube curvature are negligible.

3.2 Effects of Anisotropic Expansion

Some concern was expressed that the inability of the analyses in /1/ to adequately model blister protrusion was a result of the assumption of isotropic expansion. Consideration of the crystallographic texture in pressure tubes suggests that this assumption is not strictly true. The fabrication process results in textures such that the majority of the basal plane normals of the lattice unit cell ([0001] direction) are oriented near the tube circumferential direction/2/. This is true for both Zr-2.5Nb and Zircaloy-2 pressure tubes although the proportion is higher in Zr-2.5Nb. Zircaloy-2 pressure tubes generally have a higher proportion of basal plane normals oriented in the tube radial direction than Zr-2.5Nb tubes. In both types of tubes the proportion of basal plane normals oriented in or near both the tube radial and circumferential directions is greater than random.

It has been found/3/ that the hydride phase forms such that the orientation of the close packed planes of the hcp α-Zr lattice is maintained in the transformation to the fcc δ-hydride lattice in which hydrogen atoms occupy the tetrahedral interstices. That is, the close packed planes remain parallel in both phases: $(111)_\delta // (0001)_\alpha$; $[1\bar{1}0]_\delta // [11\bar{2}0]_\alpha$. By consideration of the apparent change in size and shape of a zirconium atom (or the α-Zr hcp unit cell) due to the phase change, it was determined in /4/ that the expansion in the direction of the basal plane normal ([0001] direction or c-axis) was 7.2% which is greater than the 4.58% calculated for expansion in the perpendicular direction ([11$\bar{2}$0] direction or a-axis). From this it could be expected that the formation of a blister would involve greater volume expansion in those tube directions having greater than average numbers of basal plane normals.

Fully anisotropic expansion can only be modelled in a three-dimensional analysis, and thus the axi-symmetric model used throughout this project is limited in this respect. However, it was possible to obtain some estimate of the effects of anisotropic expansion on blister stresses through the use of an orthotropic expansion option in the ABAQUS finite element program used. This option permits the user to specify different values of the linear expansion coefficient in each of the three principle directions.

analysis of Case A. Two other parametric cases were examined – one in which greater expansion occurred in the z-direction, and one in which greater expansion occurred in the r-θ plane. Values of the linear expansion coefficients were chosen to give a 14% volume expansion, slightly larger than the 12.5% used in Case A, and are given in Table 1. The values in Table 1 were chosen arbitrarily and are not based on known values of texture coefficients. The results at 25% of full volume expansion (or about 1% linear expansion) are compared in Figures 7 and 8.

Both figures show that increasing the amount of vertical expansion relaxes the values of the stress both within and surrounding the blister. Conversely, increasing the in-plane expansion enhances the stresses. None of these cases adequately models the anisotropy of an actual blister which could be expected to have greater expansion in both the tube radial and circumferential directions, and less in the tube axial direction. However, the results do suggest that anisotropic expansion could have a significant effect on the stresses, at least for elastic behaviour of the hydride phase.

Estimates of blister protrusion are also significantly altered by allowing anisotropic expansion. At 1% linear expansion the isotropic case predicts protrusion of 0.0103 mm. The case with greater z-direction expansion gave protrusion of 0.0141 mm while greater in-plane expansion gave a reduced protrusion of 0.0091 mm.

Although allowing for anisotropic expansion leads to reduced internal compressive stresses and improved estimates of blister protrusion, it is uncertain how large the effect of anisotropy is in a real blister.

3.3 Refinement of Material Properties in the Model

The analyses described up to this point have assumed linear-elastic behaviour for the hydride phase, and also that properties are uniform throughout the blister. These assumptions cause the internal compressive stresses to increase in magnitude with the amount of blister expansion, which makes the presence of cracks unlikely. It is thus necessary to reconsider the assumption of linear behaviour. Studies of the deformation of polycrystalline zirconium hydride/5/ have shown that at temperatures above 100°C, the δ-phase becomes ductile in compression. In addition it was found that the limit of elastic behaviour varied with both temperature and stoichiometry of the hydride phase. In tension, the behaviour was always brittle and did not vary significantly with temperature or stoichiometry. Similar behaviour has also been observed with titanium hydride/6/.

This behaviour was incorporated into the blister model as follows. Recalling that, in the finite element model, the hydrogen distribution in the blister is specified as a temperature distribution, the stress-strain relationship was specified at "temperatures" corresponding to the hydrogen concentrations of the matrix phase ([H] = 0.9 at %, T = 0) and the pure hydride phase ([H] = 60 at %; T = 100). The former used the same tensile data for Zircaloy-2 at about 200°C that was used in reference 1. Compressive strength data for the hydride phase at 200°C was obtained from Figure 1 of Reference 5, by extrapolating the curve for the deformation of $ZrH_{1.66}$ at 206°C from about 4% to 20% plastic strain. (In the analyses, plastic strain never exceeded 10%). The behaviour was assumed to vary linearly with temperature, and therefore hydrogen concentration, between these two extremes. This is shown in Figure 9. The value of the elastic modulus was also specified to permit a linear variation with hydrogen concentration, from a matrix

value of 88000 MPa to a value for hydride of 62000 MPa. Poisson's ratio was allowed to vary from 0.39 to 0.33.

Due to the nature of the ABAQUS finite element program, this approach assumes the same stress-strain behaviour in both tension and compression. This is not strictly correct but should not introduce any serious errors. The matrix phase may yield at a slightly higher stress in compression and the hydride phase will be brittle and weak in tension. The majority of stresses developed in the blister are compressive.

3.4 Analysis with Concentration Dependent Properties for the Hydride Phase

The analysis performed was similar to that of Case A described earlier/1/, except that the material properties were modified as described in section 3.3. The analysis was isotropic although the value of the linear expansion coefficient was increased to .00045 to give a full volume expansion of 14.1%.

Figure 10 shows the development of the through-thickness stresses and Figures 11 and 12 show the development of the radial and circumferential stresses, respectively, measured near the blister surface. Contour plots showing the various stress components, and the blister profile at full volume expansion are given in Appendix A.

Figures 10-12 show similar general trends. At 25% of full expansion, stresses in the core of the blister are highly compressive. The core stresses relax somewhat as volume expansion increases, although the stresses within the blister tend to become more compressive towards its boundaries. The magnitude of any tensile stresses surrounding the blister increases with increasing expansion.

This type of behaviour is at least partially dependent on the method of analysis. Volume expansion is obtained by specifying a temperature field to determine the appropriate thermal expansion at a point. The finite element program obtains solutions for proportional temperature fields scaled to 25%, 50%, 75% and 100% of the field that gives the full 14.1% volume expansion. This will occur when the maximum temperature, which gives the properties of the pure hydride phase, has a non-dimensional value of 100. At T = 0 the properties will be those of the matrix. At intermediate "temperatures" (hydrogen concentrations) the properties will be interpolated, as explained in section 3.3. Thus when a solution is obtained for 50% of full volume expansion, the maximum "temperature" of the imposed temperature field will be 50 and the properties of the blister core will lie in the line indicated as T = 50 in Figure 9. Further away from the blister core the properties will approach the matrix properties given by the line T = 0. Thus, in reality, a solution will have been obtained for a blister having 50% of the density of a full grown blister.

It is interesting to note that the magnitude of the compressive stresses at the core of the blister actually decreases with increasing volume expansion. This is a result of relaxation of the stresses as the material yields. The stress at which yielding occurs is determined by the hydrogen concentration. Thus while the stresses in the core region relax, those in the material near the blister boundary become more compressive because the hydrogen concentration in this region remains low. Thus

the material properties are similar to those of the matrix and higher stresses can be sustained without yielding.

It should also be noted that superimposing a stress having the magnitude of the operating hoop stress would probably be sufficient to make the stresses tensile. It should thus be relatively simple to initiate cracking. The fact that the stresses are more compressive at the blister boundary explains why cracks in most blisters do not penetrate to the full depth of the blister.

Figure 13 shows a plot of blister protrusion for this case compared with that for Case A from reference 1. The introduction of elastic-plastic behaviour to the blister permits bulging that is at least 50% greater. Some of the increase can be attributed to the larger volume expansion (14.1% vs 12.5%), but most must be due to yielding of the hydride phase. The larger protrusion is much closer to that expected, based on measured profile heights of laboratory-grown Zircaloy-2 blisters, which showed that the ratio of profile height to blister depth was about 0.1.

The decreasing compressive stresses at the blister core may also partly be due to the effect of bulging. This leads to stretching of the outer surface of the blister, and could eventually lead to tensile outer surface stresses and strains. This possibility has been discussed previously and was proposed as a possible mechanism for crack nucleation and growth in blisters/7/.

4.0 ANALYSIS INVOLVING THE Zr-2.5 Nb MESH AND A HYDROGEN DISTRIBUTION OBTAINED FROM BLISTER GROWTH MODELLING

Although the model remains fairly simplistic, the results of the analyses described in section 3 have led to predictions of stresses and protrusions that are consistent with observations made on blisters from reactor and those grown in the laboratory.

However, as a further test of the model, an attempt was made to model a laboratory-grown blister for which the hydrogen distribution had been estimated by a numerical simulation of blister growth/8/. Profile measurements had also been made on this particular blister and could thus be compared with the results of the analysis.

4.1 Material Properties

The same approach was used to incorporate the dependence of the properties of the hydride phase on the hydrogen concentration into the model as outlined in section 3.3. A linear variation with temperature (hydrogen concentration) was assumed between the properties of the matrix and those of the δ-hydride phase at approximately 200°C. This is shown in Figure 14. As before, a temperature of T = 100 will result in full 14.1% volume expansion and give properties of pure hydride. At T = 0 there will be no expansion and the properties will be those of the matrix. (Recall from section 2.2 that the temperature field is directly proportional to the hydrogen concentration). The same properties were used for the hydride phase as in the previous analysis but the strength of the matrix was increased to reflect the higher strength of Zr-2.5Nb. The matrix properties are taken as an average of transverse and axial properties.

4.2 Interpolation of the Hydrogen Distribution

An analysis was performed using a finite difference program for modelling blister growth based on an axi-symmetric model/8/. The growth analysis was based on the conditions used to grow the blister shown in Figure 15. Figure 16 shows a plot of the hydrogen concentration distribution predicted by the model for comparison.

This analytical distribution was transferred to the finite element program for expansion modelling by the following method. The hydrogen concentrations at the nodal locations of the finite difference mesh were entered into an interpolation program. This program compared the nodal coordinates of the finite element mesh with those of the finite difference mesh and interpolated the concentration values between the finite difference nodes to obtain values for the nodes of the finite element mesh. A list of nodal temperatures varying from T = 100 ([H] = 16000 ppm or 60 at %) to T = 0 ([H] = 100 ppm or 0.9 at %) was output for the nodes in the blister region. This was used as input to the finite element analysis program. A plot of the resulting temperature distribution is shown in Figure 17 and is similar in shape to the hydrogen concentration profiles in Figure 16.

4.3 Predicted Stresses

The analysis was isotropic, with an expansion coefficient of 0.00045, giving a full volume expansion of 14.1% at T = 100. Figures 18, 19 and 20 show the development of the through-wall, surface radial and surface circumferential stresses at 25%, 50%, 75% and 100% of full expansion.

Comparing Figure 18 with Figure 10 shows that while the overall pattern of the through-wall stresses is similar in both cases, the Zr-2.5Nb case predicts that stresses actually become tensile at the blister core. In addition, the maximum compressive stresses do not get larger with greater expansion but remain constant. The transition from compressive to tensile stress occurs over much narrower range, and the tensile stresses beneath the blister are seen to decrease with increasing expansion, the opposite from what was observed with the Zircaloy-2 mesh.

Comparing surface radial and circumferential stresses for the two cases shows that the stresses for the Zr-2.5Nb case with the analytical hydrogen distribution remain essentially constant within the blister, becoming less compressive with increasing expansion. For the Zircaloy-2 case with the assumed cosine hydrogen distribution, the stresses become more compressive with distance from the blister centre. Again the transition from compressive to tensile stress at the blister boundary is more rapid with the Zr-2.5Nb analysis.

Near the surface, maximum values of the tensile circumferential stresses in the matrix surrounding the blister are higher for the Zr-2.5Nb case. This may however be due to numerical instability in the model as a result of not having a fine enough mesh in the region where the hydrogen concentration decreases very rapidly. The concentration decreases more gradually with the cosine distribution, and no such instabilities were encountered. The lines showing the tensile peaks just beyond the blister boundary in Figure 20 were arbitrarily smoothed and do not show the fluctuation of the stresses in this region.

Figure 21 shows the fluctuation of the circumferential stress values obtained at the element integration points for the 100% case of Figure 20. It can be seen that

there is some fluctuation of stresses surrounding the rapid transition from compressive to tensile stress at the blister boundary. The assumed stress profile that was given in Figure 20 is indicated. It was assumed that the stresses approach the maximum tensile and compressive values although it is possible that the actual stress transition is more gradual. The boundary stresses were represented as being discontinuous in Reference 1. A finer mesh will be required to resolve this problem in future analyses.

Stress contour plots showing the radial, circumferential, shear and equivalent stresses and the profile at full volume expansion are included in Appendix B.

4.4 Predicted Protrusion

The predicted blister protrusion, determined from nodal displacements, is compared with actual profile measurements in Figure 22. The agreement is good although the finite element analysis under-predicts the protrusion the blister centre. This may be due to an effect of anisotropy or a variation in the actual hydrogen distribution from that used in the analysis. It may also be a result of the assumption of a linear variation in compressive strength properties with hydrogen concentration.

4.5 Anisotropy

The preceding analysis was repeated to give increased expansion in the r-θ plane. Orthotropic expansion was used in the same manner as explained in section 3.2. The linear expansion coefficient was arbitrarily chosen as .00055 in both the radial and circumferential directions and .00025 in the vertical (z) direction, giving a full volume expansion of 14.1% at T = 100.

No significant difference was found in the stresses or the blister profile between the two cases. Figure 23 compares the circumferential stress profiles at the full 14.1% expansion. The stresses within the blister are slightly more compressive and the peak tensile stress at the blister boundary is slightly increased for the anisotropic case. This indicates that the material properties of the hydride phase have a far greater effect on the expansion stresses and blister protrusion than any effect of anisotropic expansion could have. Blister protrusion will probably also be affected by the hydrogen distribution.

5.0 DISCUSSION

Some general observations regarding the nature of blister expansion stresses were summarized in Reference 1. The most important differences between the earlier analyses and those reported here are a result of modifications to the material properties to permit yielding of the hydride phase in compression. This behaviour has been observed in detailed studies of the deformation of zirconium hydride at temperatures above 100°C/5/. It has been estimated that the minimum temperature of the region of a pressure tube in contact with a calandria tube is about 200°C. Thus, this behaviour could reasonably be expected in blisters grown in reactor. It should also be noted that the deformation behaviour varies with the stoichiometry or hydrogen concentration of the hydride phase. In the absence of detailed information on this variation, the properties were assumed to vary linearly with hydrogen concentration from those of the matrix to those of the δ-hydride phase. The true variation is almost certainly not linear, but this assumption is a reasonable first approximation.

One of the interesting consequences of this assumption, which is in part due to the solution technique of the finite element program, is that the stresses can be shown to vary with the density of the blister. (The term density has been used throughout to refer to the hydrogen concentration). The internal stresses are most highly compressive for the least dense blisters, which have properties close to those of the matrix and can thus support larger stresses. As density increases, the properties approach those of the pure hydride and the internal compressive stresses are relaxed due to yielding. Some of the reduction in compressive stress near the blister surface is also due to increased protrusion which increases the strain at the blister surface. However, the increased protrusion is a result of yielding.

These observations have some experimental support from the results of cracking tests that showed that the stress to crack a blister decreases with increasing blister size/9/. If it is true that smaller blisters are also generally less dense, then the experimental observations can be explained in terms of the necessity to apply a stress large enough to overcome the internal compressive stresses before cracking can occur. Note that for full grown blisters, the internal compressive stresses are predicted to become small enough for the operating hoop stress to cause cracking.

The age-density relationship has some support from the results of room temperature microhardness measurements performed on blisters grown in-reactor. Peak hardnesses were higher for blisters at the centre of contact regions than those at the edge, which presumably formed later/10/. Higher hardness appears to indicate a higher hydrogen concentration. While it is likely that younger and smaller blisters are not simply less dense versions of older and larger ones, the concept may be of some value for understanding blister behaviour. This effect could be analysed more precisely by performing a series of analyses using hydrogen distributions obtained from growth modelling analyses for different time intervals. Other work planned in the future includes a three-dimensional analysis and analysis of a cracked blister.

6.0 CONCLUSIONS

The following conclusions can be drawn from the results of the analyses summarized in this report.

1. Modifications to the model to allow compressive yielding of the hydride phase and hydrogen concentration dependence of the material properties have provided estimates of blister expansion stresses that are consistent with observations. Specifically:

   i) Internal compressive stresses are reduced sufficiently to make cracking conceivable;

   ii) Blister protrusion can be modelled with reasonable accuracy; and

   iii) An explanation has been provided for the experimental observation that the stress to crack blisters decreases with increasing blister size.

2. Compressive yielding of the hydride phase reduces compressive stresses within the blister in two ways:

i) Yielding simply relieves stresses and presents further stress increase; and

ii) Yielding results in greater protrusion which increases the strain at the blister surface, and can lead to tensile stresses at the surface.

3. Anisotropic expansion can significantly alter elastic expansion stresses, but is unlikely to be important if plastic deformation occurs.

4. A realistic estimate of the blister hydrogen distribution can be incorporated into the model.

7.0 ACKNOWLEDGEMENTS

This work is part of the TRAC* Task 412 – Simulation of Blister Growth Due to Contact. The useful discussions with Mr. M.L. Vandergias and Dr. Y.J. Kim at the outset of the project are gratefully acknowledged as are the discussions with Dr. M. Leger of the Materials Integrity Section. Special recognition is due to Dr. Y.J. Kim who prepared much of the basic model used for the analyses and also to a summer student, Mr. Z. Perkons for writing an interpolation program that worked.

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*TRAC – Tube Response After Contact.

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8. Byrne, T.P. and Leger, M., "Hydride Blister Growth Modelling – Progress Report No. 2", Ontario Hydro Research Division Report No. 85-29-H, File 825.21.

9. Wallace, A.C., "Experimental Investigation of the Cracking of Zirconium Hydride Blisters Grown on Zr-2.5% Nb Pressure Tube Material – TRAC Task 415/16.01 Progress Report 1", Ontario Hydro Research Division Report No. 86-159-K, File 826.231, July, 1986.

10. Wallace, A.C. and Rodgers, D.K., "Crack Initiation at Zirconium Hydride Blisters", Proceedings of AECL Fuel Channel Technology Seminar, Oakville, Ontario, November 12-14, 1985 (in preparation).

TABLE 1

Values of Linear Expansion Coefficients
Used to Investigate Anisotropy

Case	α_{rr}	$\alpha_{\theta\theta}$	α_{zz}
Isotropic	.0004	.0004	.0004
Greater Radial Expansion	.0003	.0003	.00075
Greater In-Plane Expansion	.0006	.0006	.00015

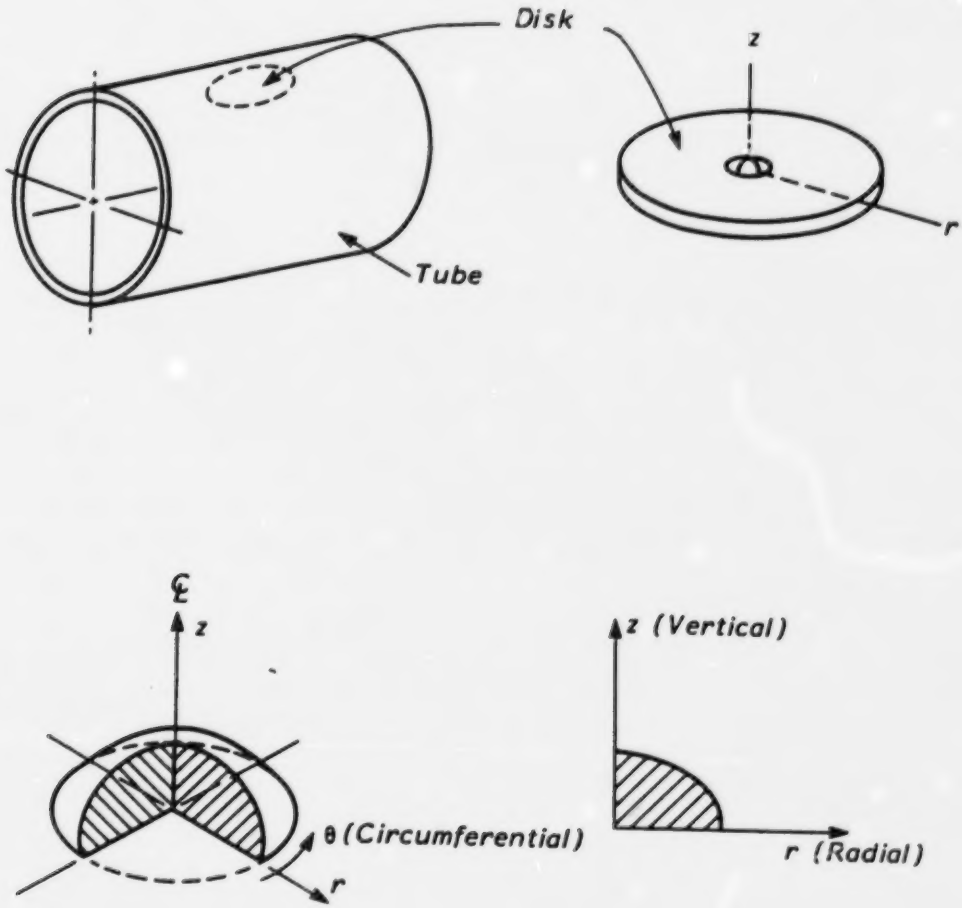
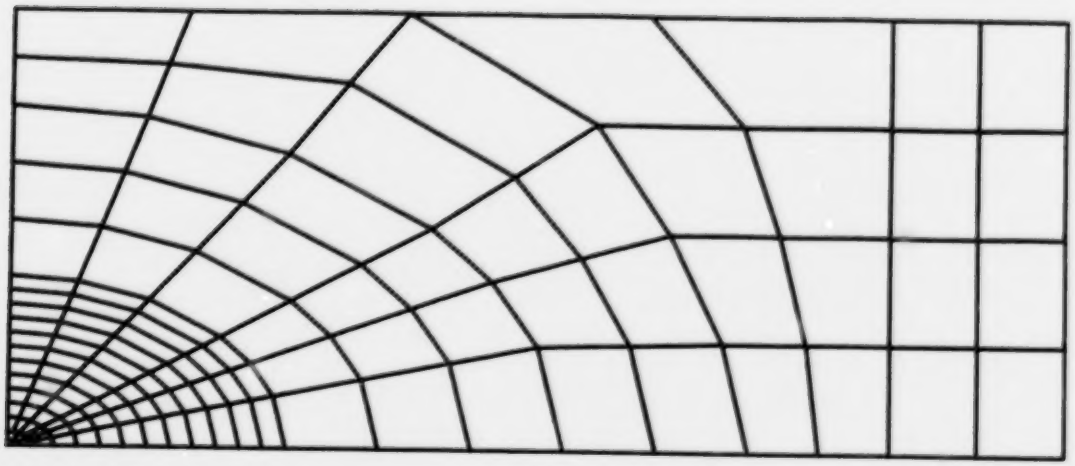
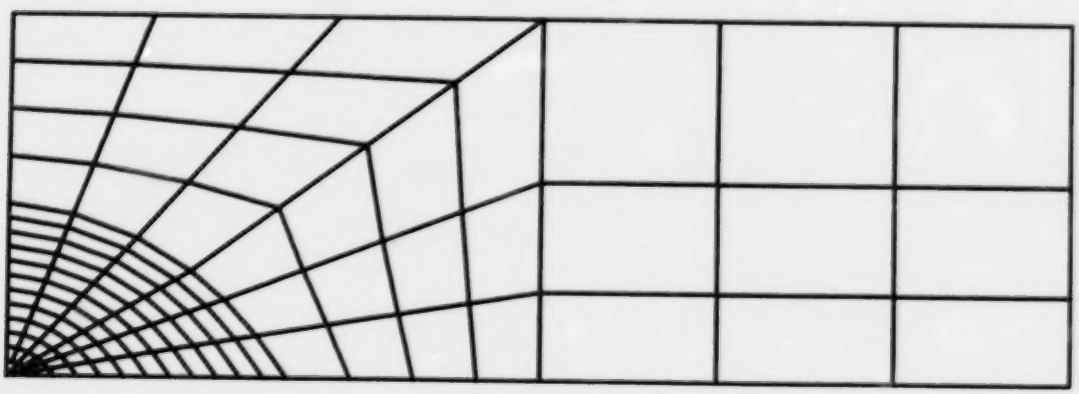


FIGURE 1

AXISYMMETRIC MODEL SHOWING HOW BLISTER IS MODELLED AT CENTRE OF FLATTENED DISK OF MATERIAL "CUT" FROM A PRESSURE TUBE. RADIAL, CIRCUMFERENTIAL AND VERTICAL (THROUGH-WALL) DIRECTIONS ARE INDICATED.



a) Zircaloy-2 Mesh



b) Zr-2.5Nb Mesh

FIGURE 2
FINITE ELEMENT MESHES USED IN THE ANALYSES

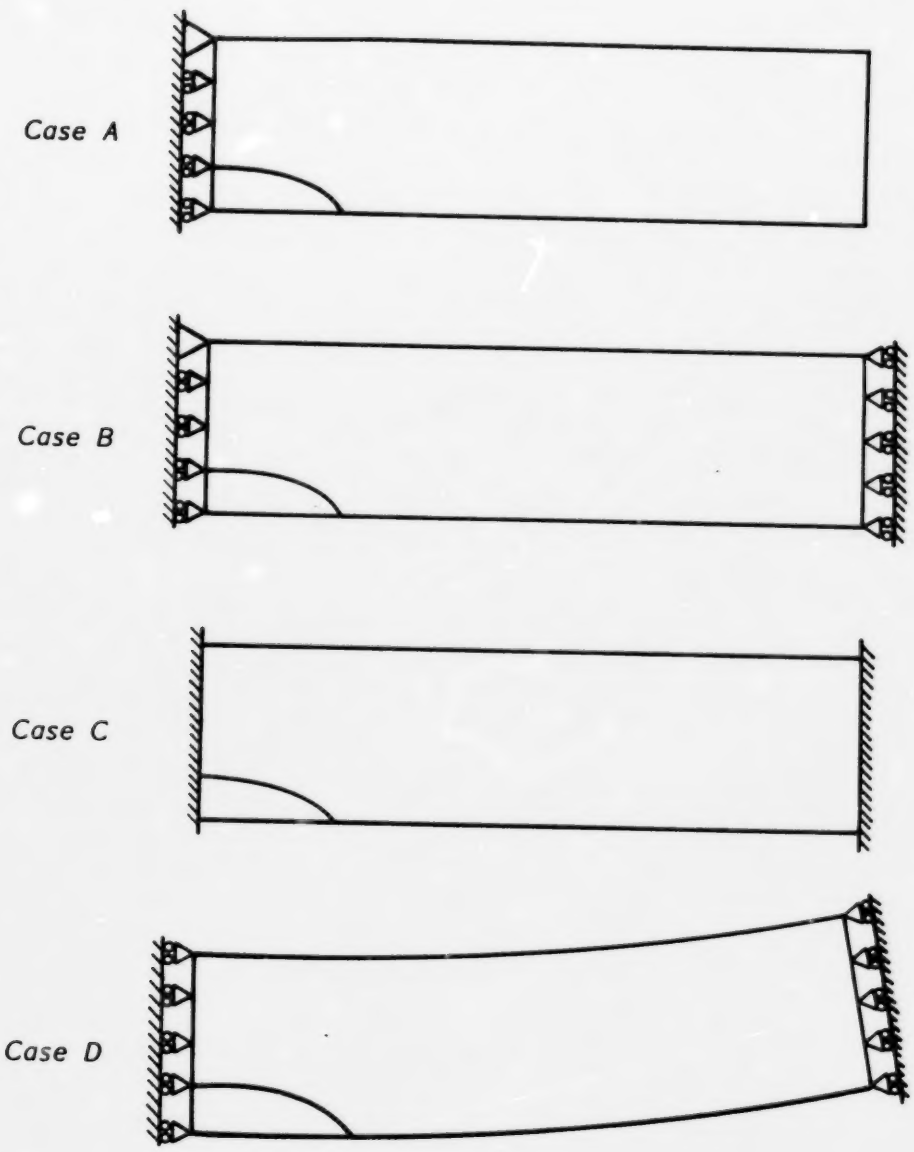
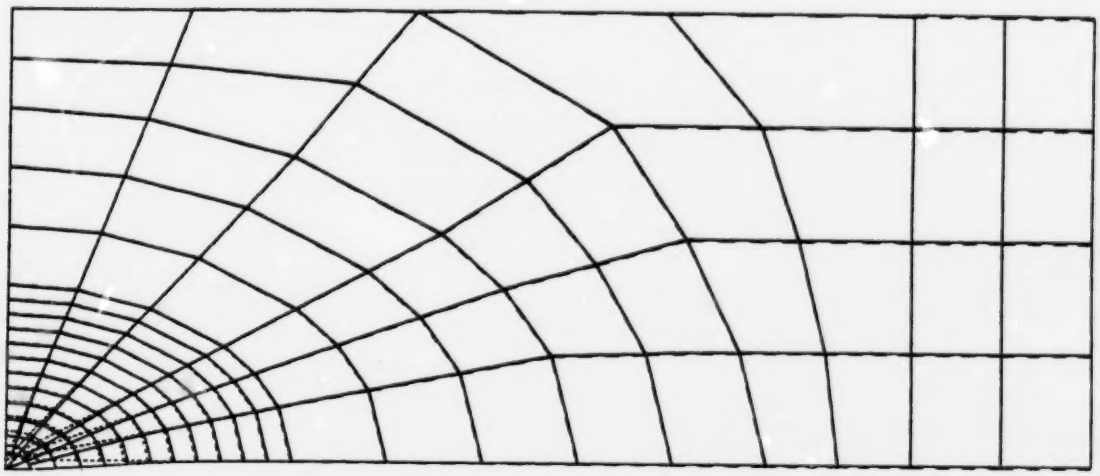
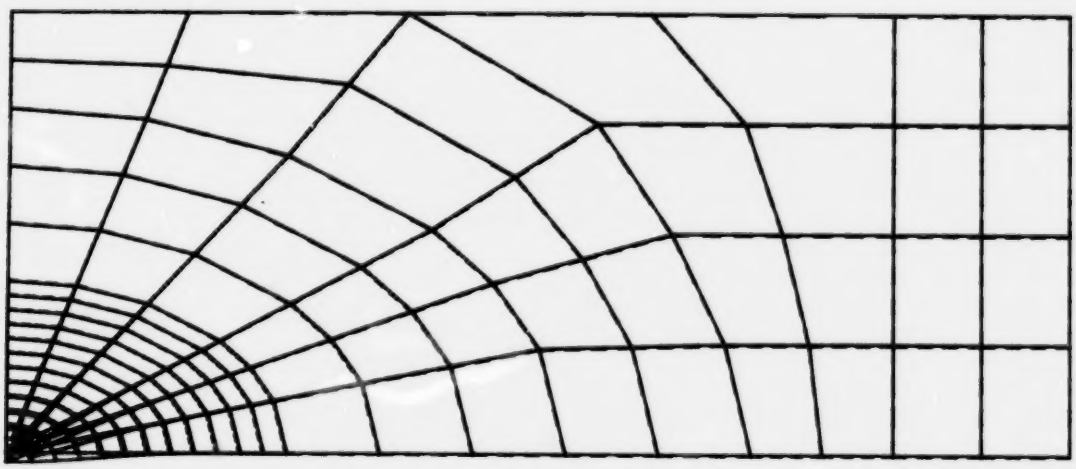


FIGURE 3

ILLUSTRATION OF THE DIFFERENT TYPES
OF BOUNDARY CONDITIONS EXAMINED



a) Case A

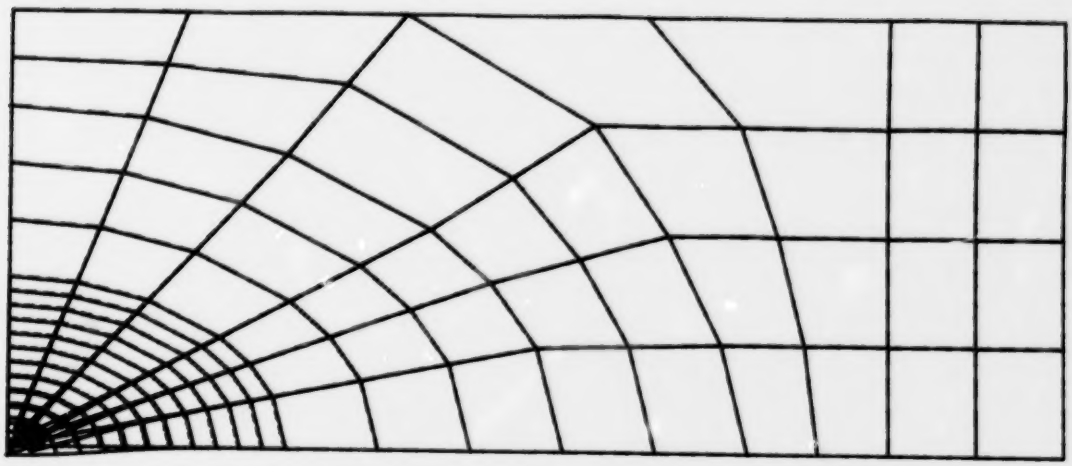


b) Case B

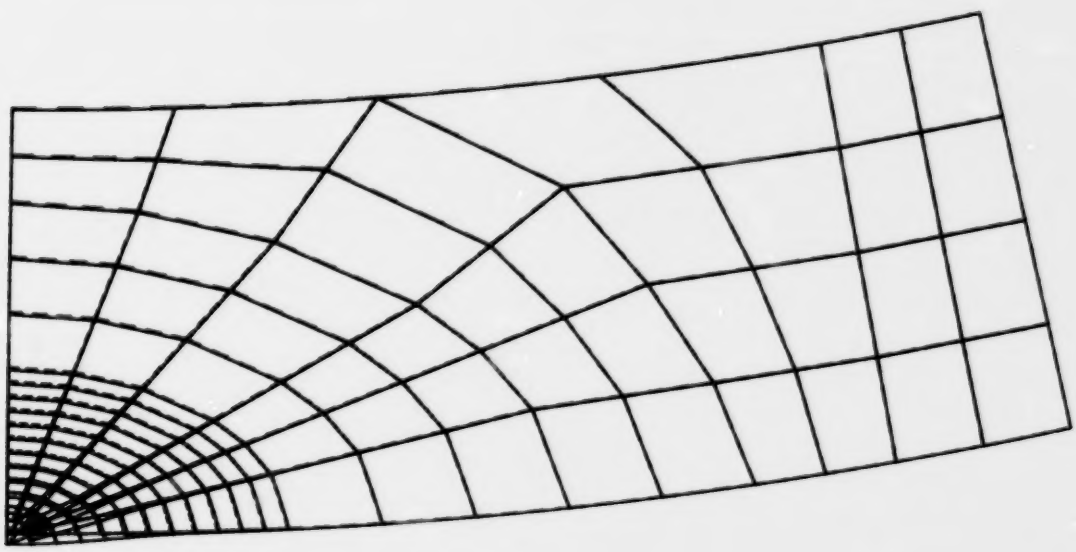
FIGURE 4

COMPARISON OF DISPLACED MESHES FOR DIFFERENT BOUNDARY CONDITIONS AT 1% LINEAR EXPANSION

- displacements magnified x 10
- solid line - displaced mesh
- broken line - original mesh



c) Case C



d) Case D

FIGURE 4 (Continued)

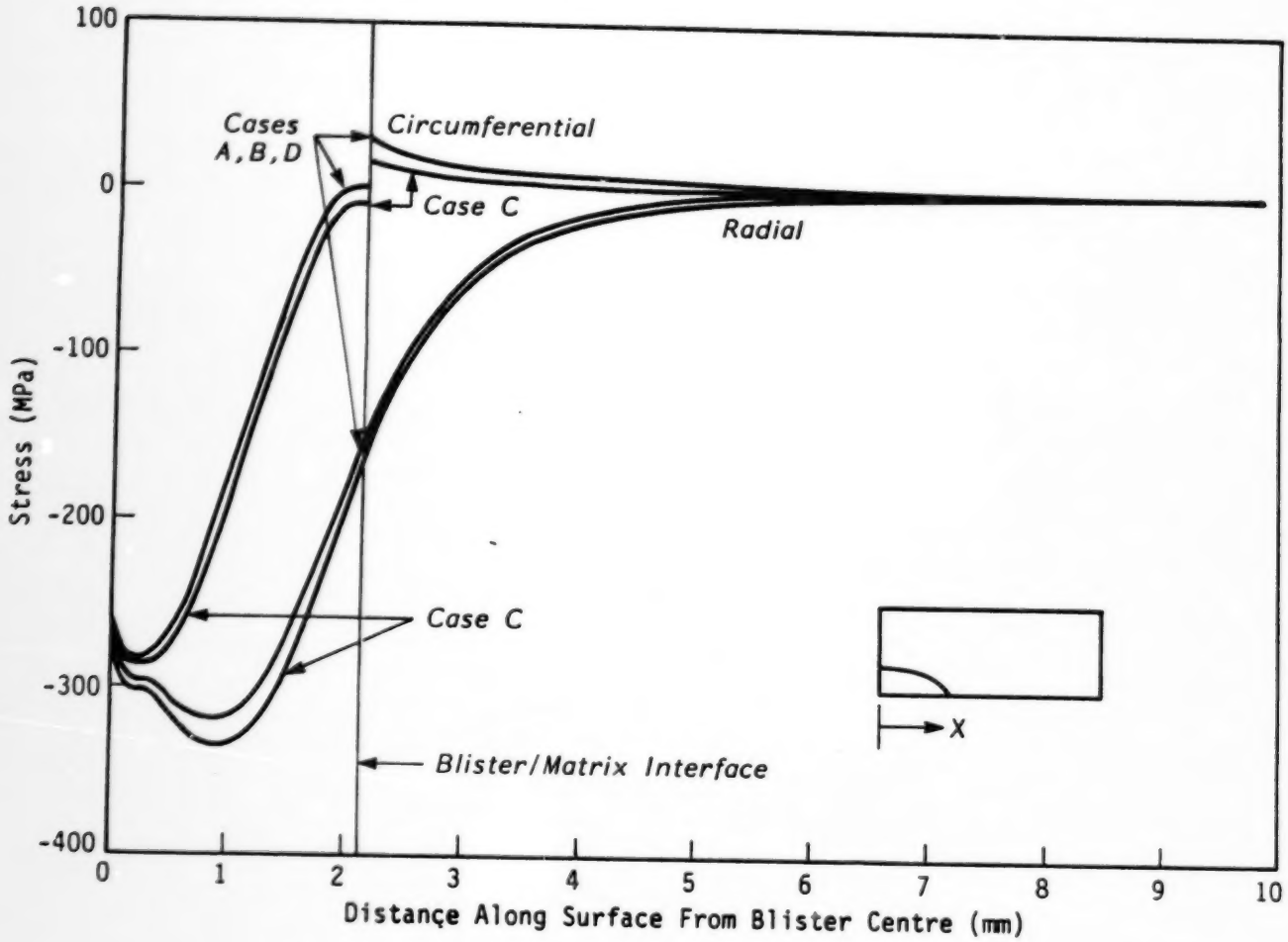


FIGURE 5

EFFECTS OF VARIATIONS IN BOUNDARY CONDITIONS ON RADIAL AND CIRCUMFERENTIAL SURFACE STRESSES AT 1% LINEAR EXPANSION

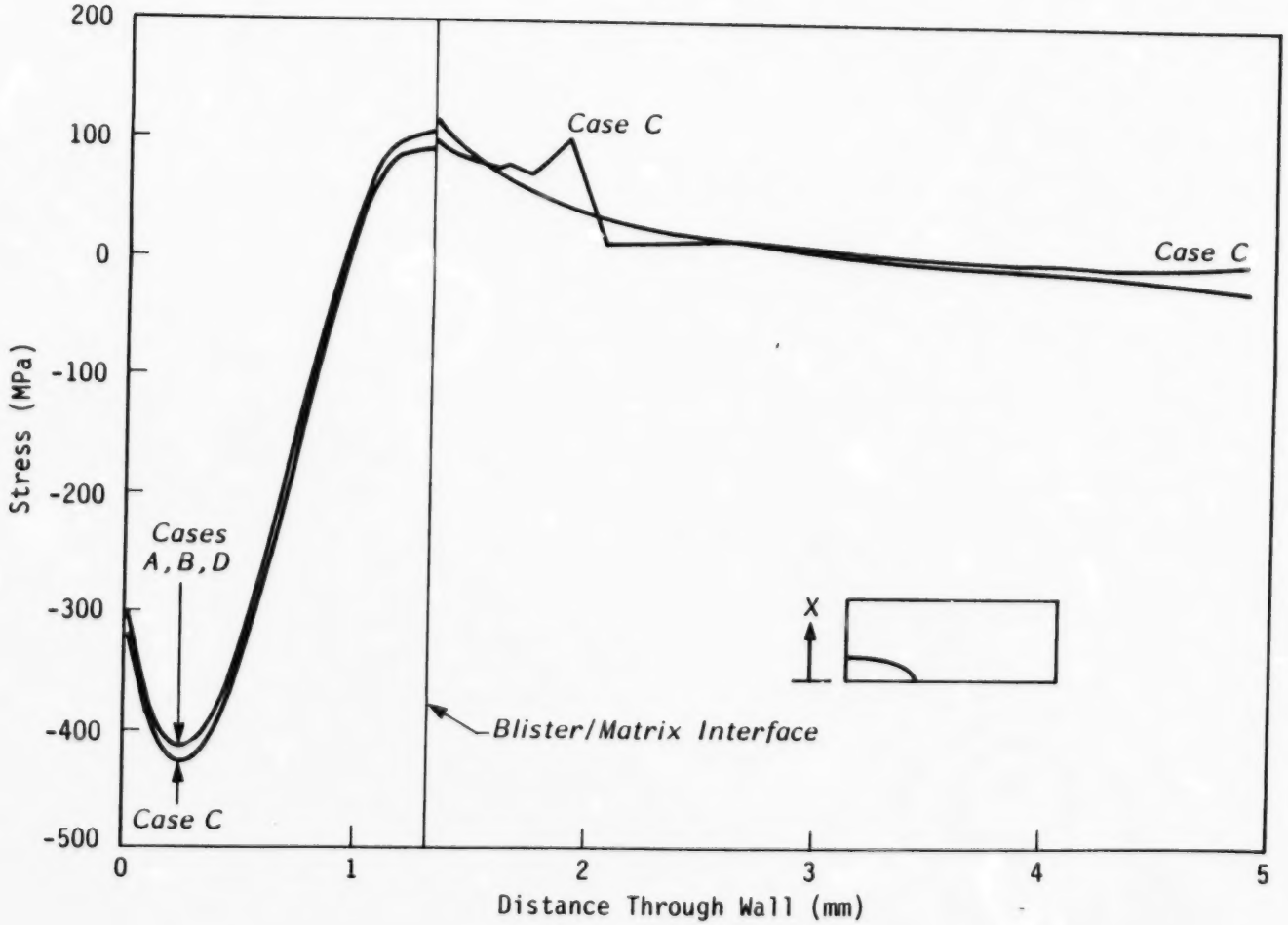


FIGURE 6

EFFECTS OF VARIATIONS IN BOUNDARY CONDITIONS ON THROUGH WALL STRESSES ALONG AXIS OF SYMMETRY AT 1% LINEAR EXPANSION

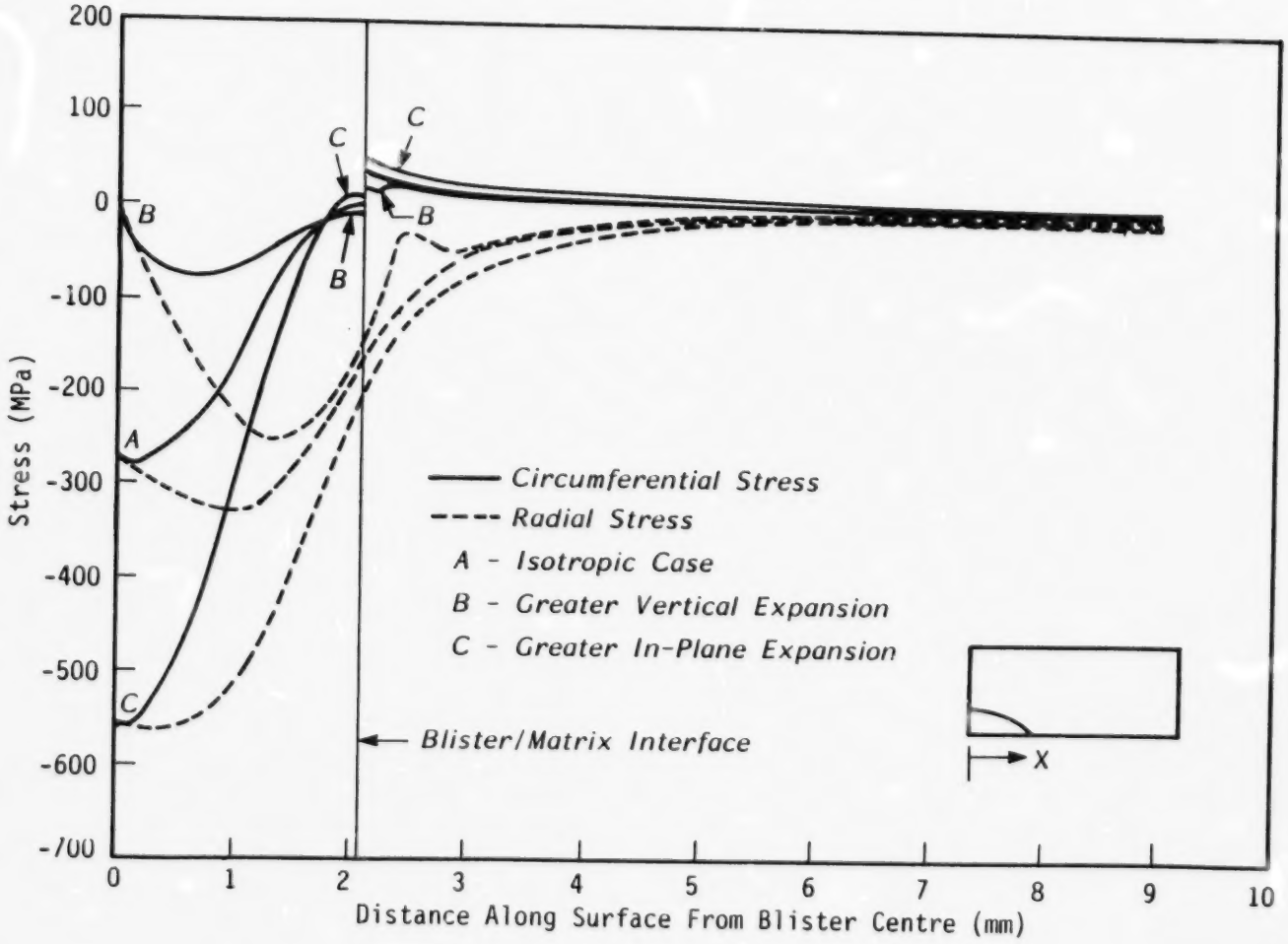


FIGURE 7

EFFECTS OF ANISOTROPIC EXPANSION ON RADIAL AND CIRCUMFERENTIAL SURFACE STRESSES AT 1% LINEAR EXPANSION

172109 R

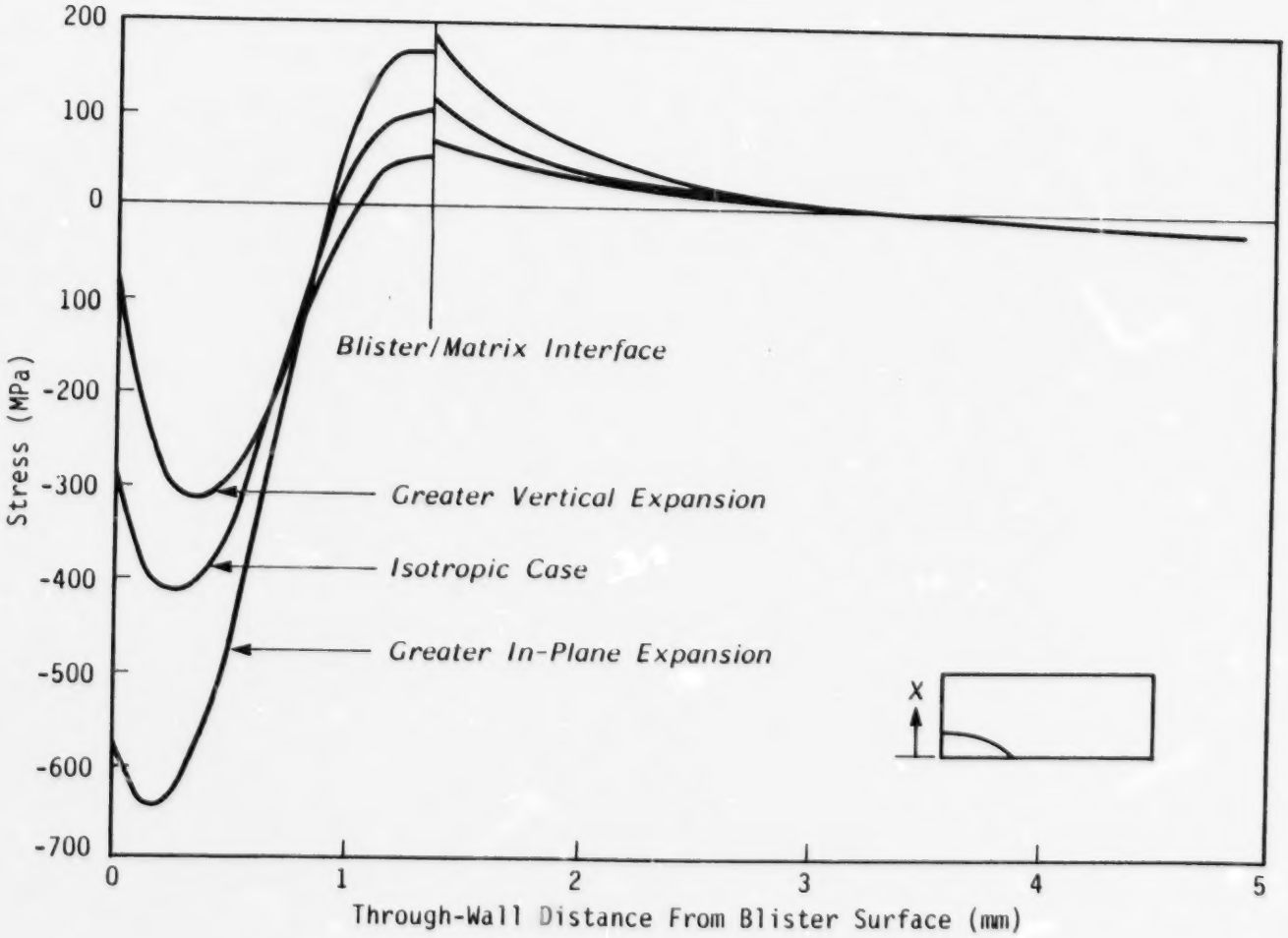


FIGURE 8

EFFECTS OF ANISOTROPIC EXPANSION ON
THROUGH-WALL STRESSES AT 1% LINEAR EXPANSION

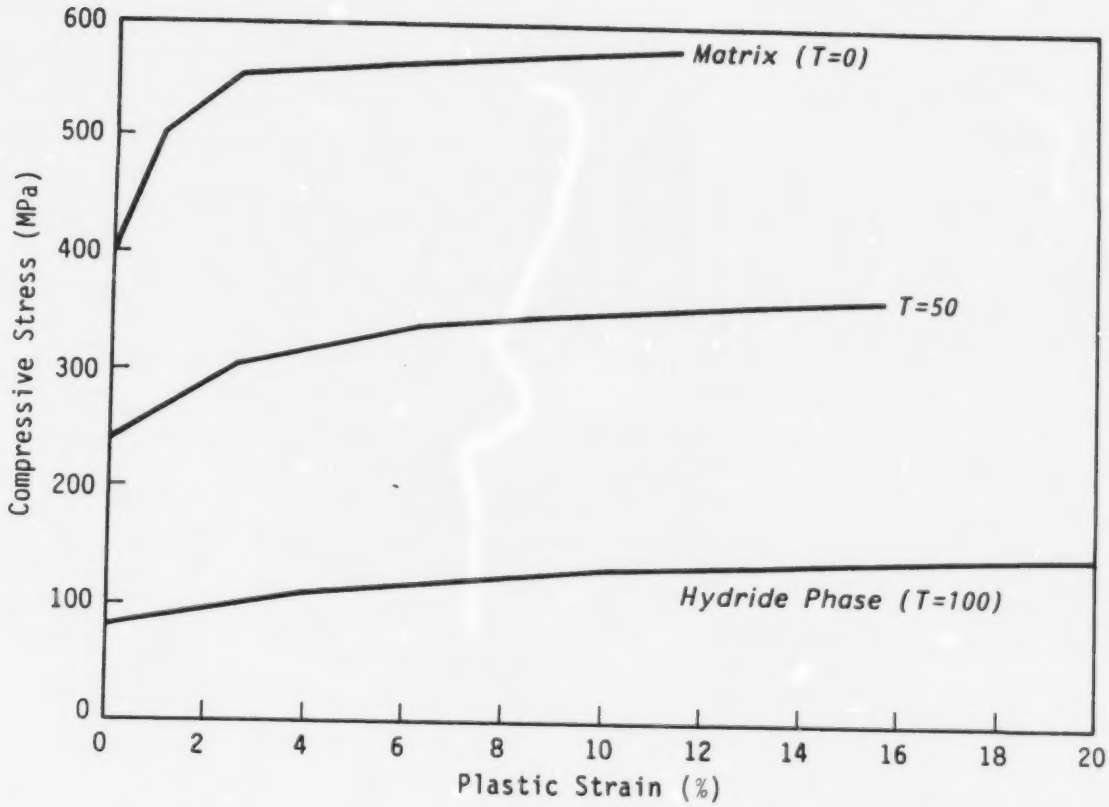


FIGURE 9

VARIATION OF MATERIAL STRESS-STRAIN PROPERTIES WITH HYDROGEN CONCENTRATION AT ABOUT 200°C (USED IN ANALYSES WITH ZIRCALOY-2 MESH)

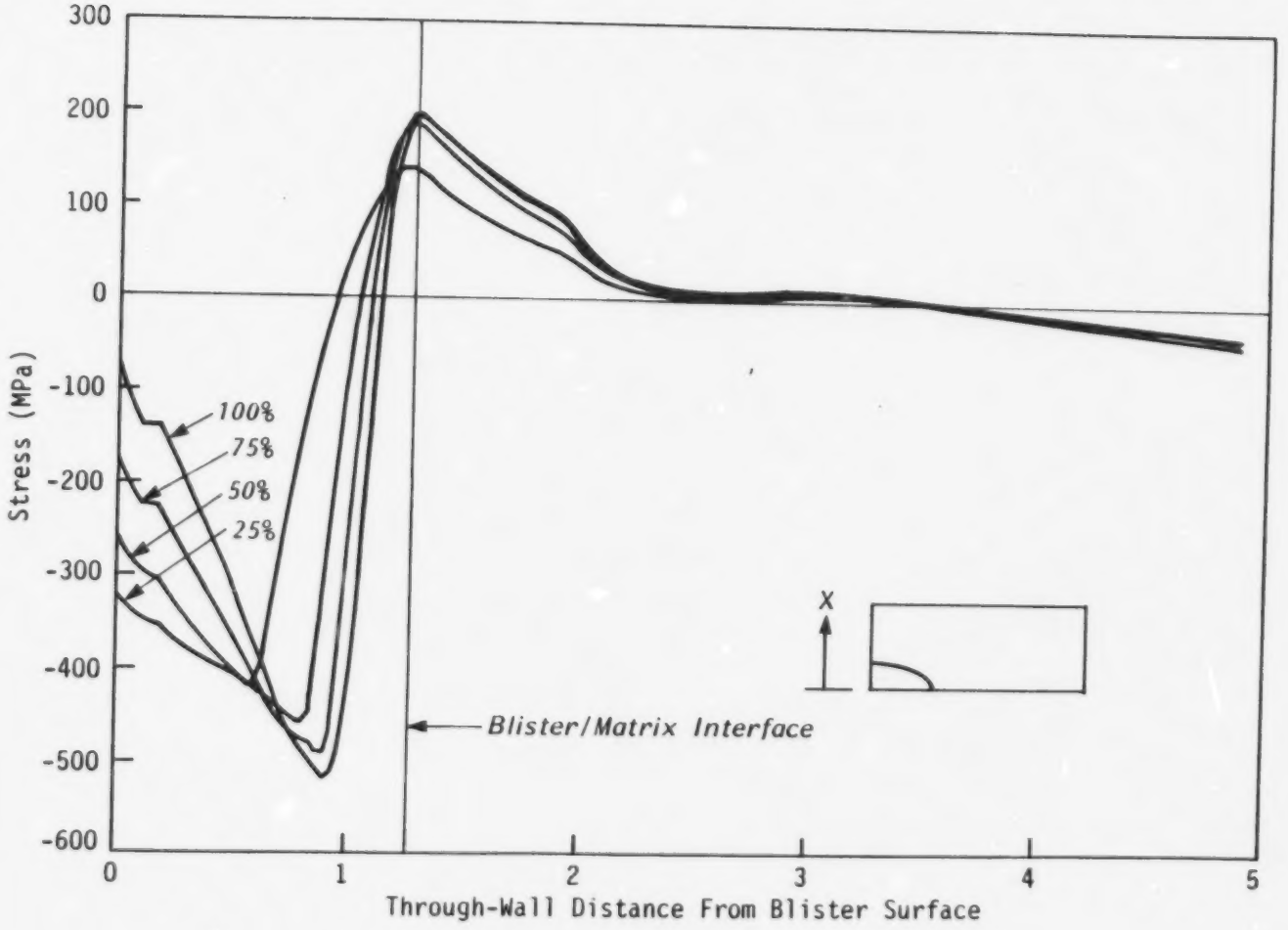


FIGURE 10

DEVELOPMENT OF THROUGH-WALL STRESSES WITH INCREASING VOLUME EXPANSION FOR ZIRCALOY-2 MESH WITH A COSINE HYDROGEN DISTRIBUTION AND CONCENTRATION DEPENDENT MATERIAL PROPERTIES

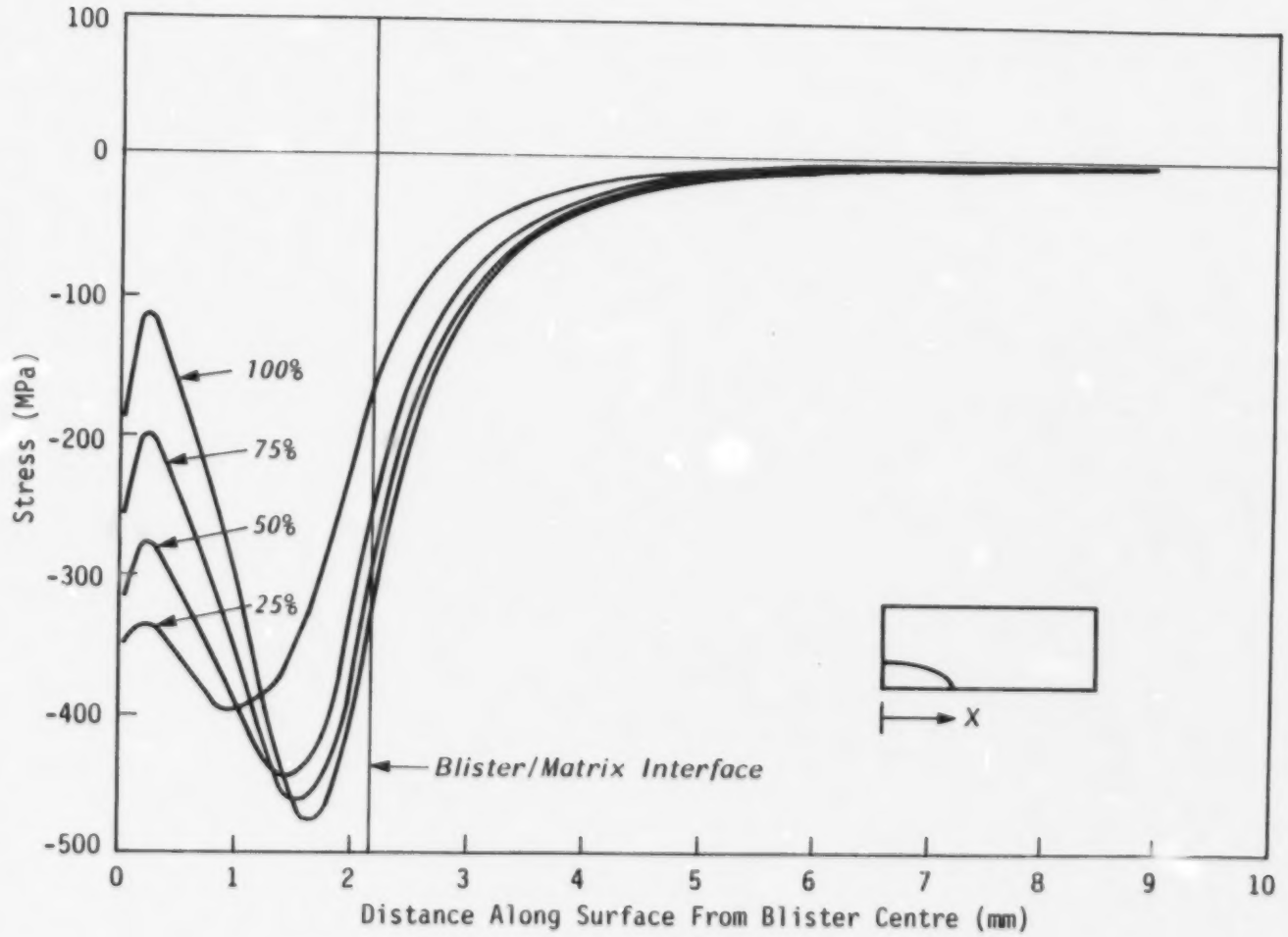


FIGURE 11

DEVELOPMENT OF SURFACE RADIAL STRESSES WITH INCREASING VOLUME EXPANSION FOR ZIRCALOY-2 MESH WITH COSINE HYDROGEN DISTRIBUTION AND CONCENTRATION DEPENDENT MATERIAL PROPERTIES

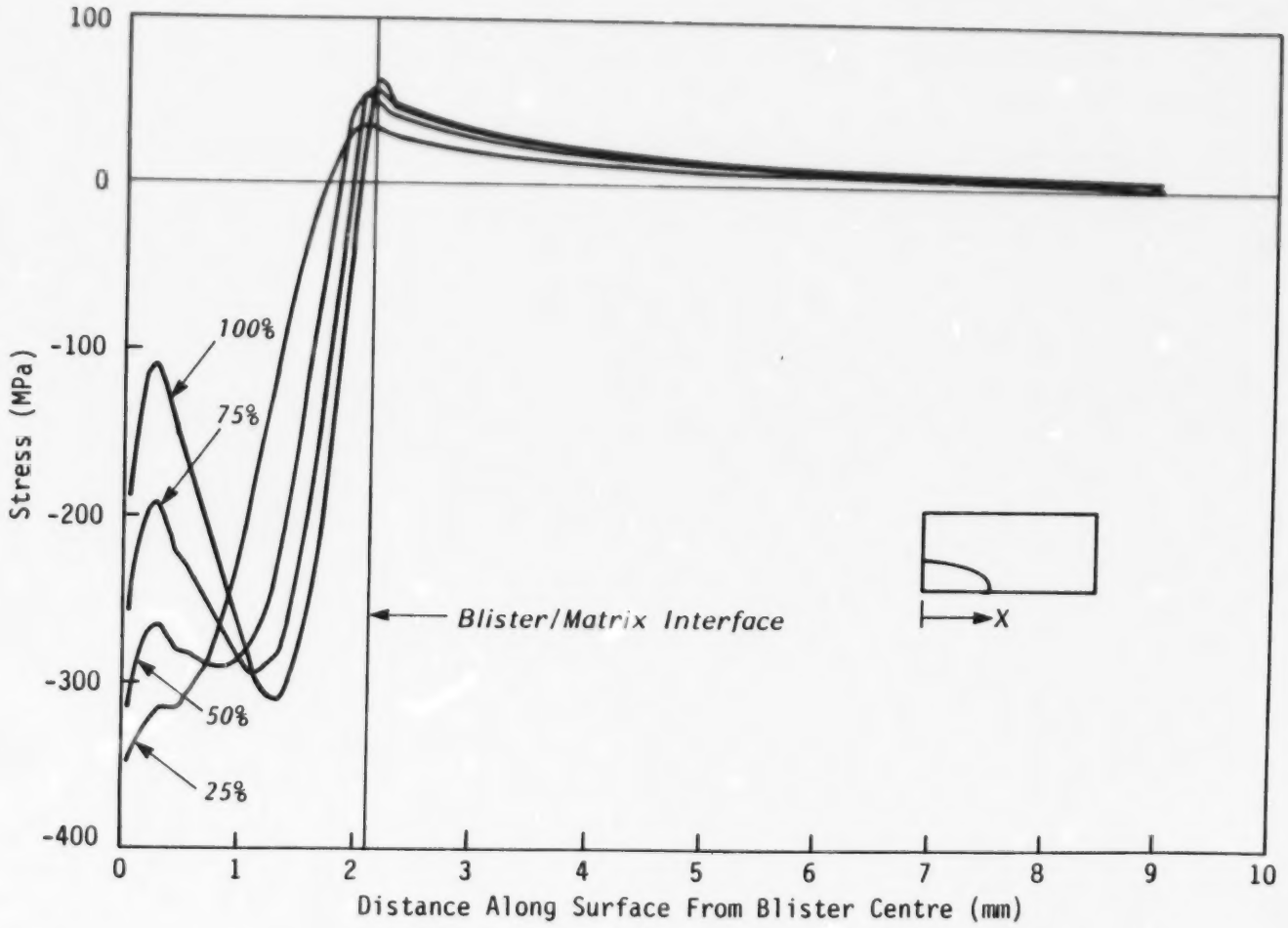


FIGURE 12

DEVELOPMENT OF SURFACE CIRCUMFERENTIAL STRESSES WITH INCREASING VOLUME EXPANSION FOR ZIRCALOY-2 MESH WITH A COSINE HYDROGEN DISTRIBUTION AND CONCENTRATION-DEPENDENT MATERIAL PROPERTIES

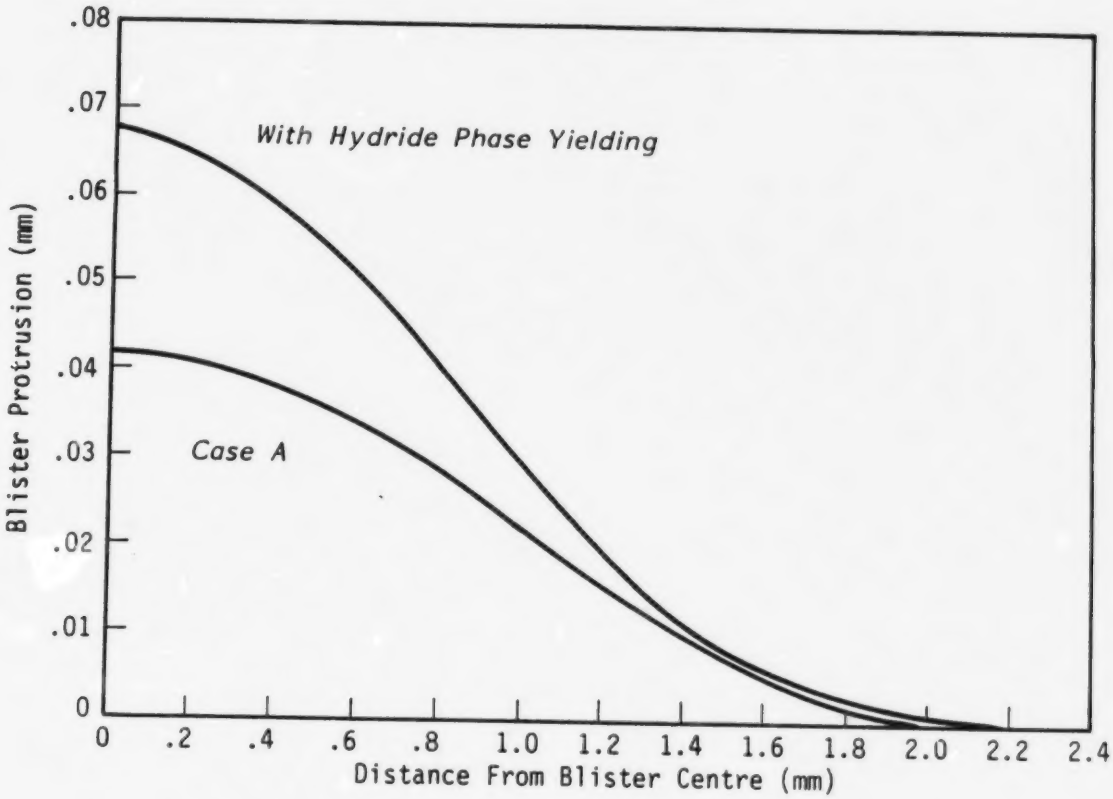


FIGURE 13

COMPARISON OF BLISTER PROTRUSION FOR ANALYSIS WITH CONCENTRATION DEPENDENT MATERIAL PROPERTIES AND A BLISTER WITH CONSTANT, ELASTIC PROPERTIES

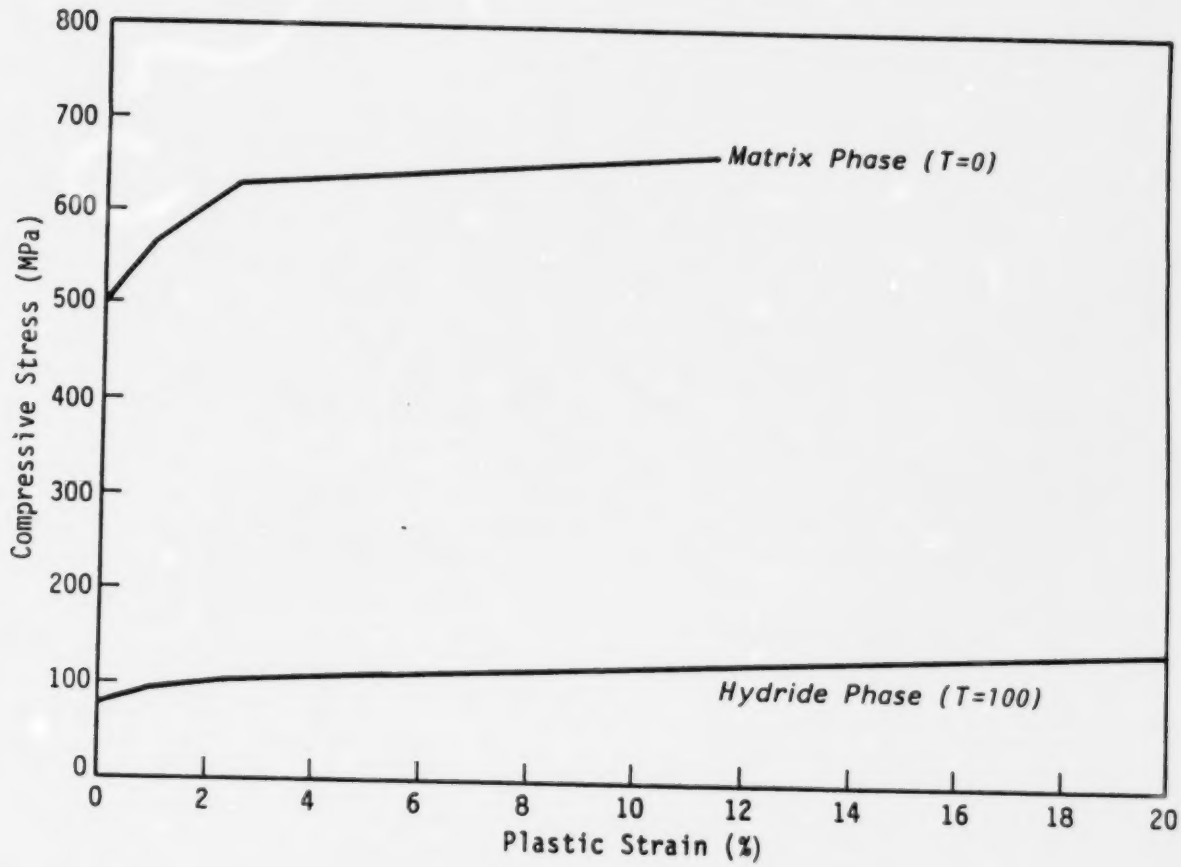
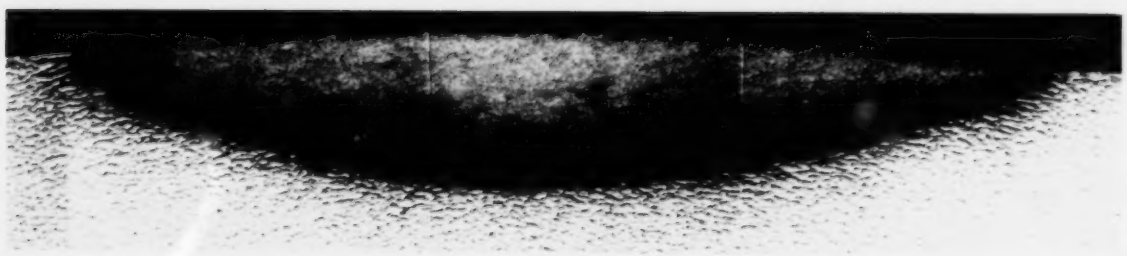


FIGURE 14

VARIATION OF MATERIAL STRESS-STRAIN PROPERTIES WITH HYDROGEN CONCENTRATION AT ABOUT 200°C (USED IN ANALYSIS WITH THE Zr-2.5 Nb MESH)

FIGURE 15

HYDROGEN CONCENTRATION CONTOURS OBTAINED FROM FINITE DIFFERENCE BLISTER GROWTH MODELLING ANALYSIS. THIS DISTRIBUTION WAS USED AS INPUT FOR THE FINITE ELEMENT ANALYSIS. CONTOURS SHOWN ARE: 10000, 5000, 1000, 500, AND 200 ppm



X30

FIGURE 16

PHOTOGRAPH OF A DEUTERIDED BLISTER GROWN FOR 42 DAYS THAT WAS MODELLED TO GIVE THE CONTOURS SHOWN IN FIGURE 15

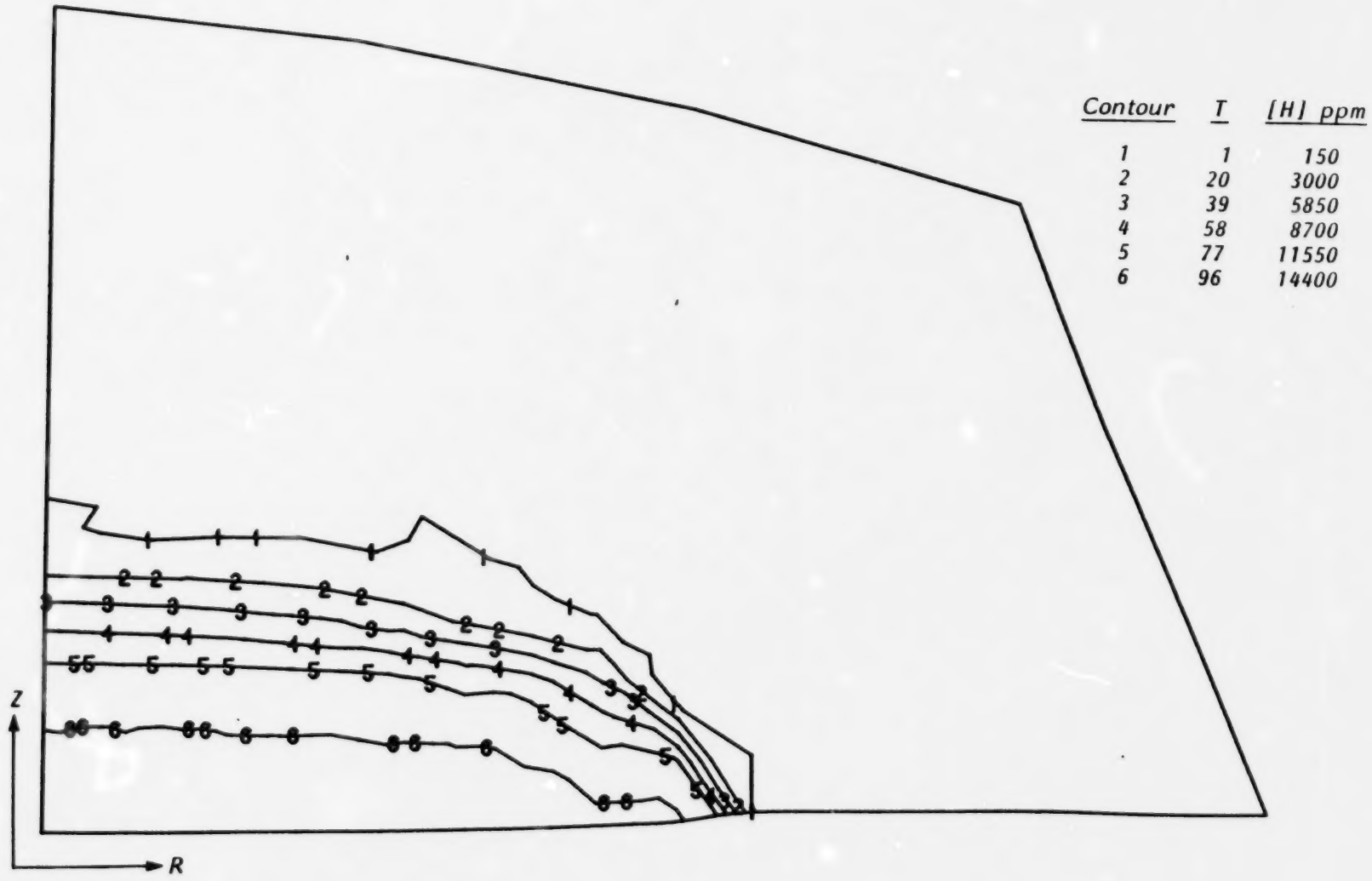


FIGURE 17

INTERPOLATED TEMPERATURE DISTRIBUTION
USED TO MODEL THE HYDROGEN DISTRIBUTION

122117 R

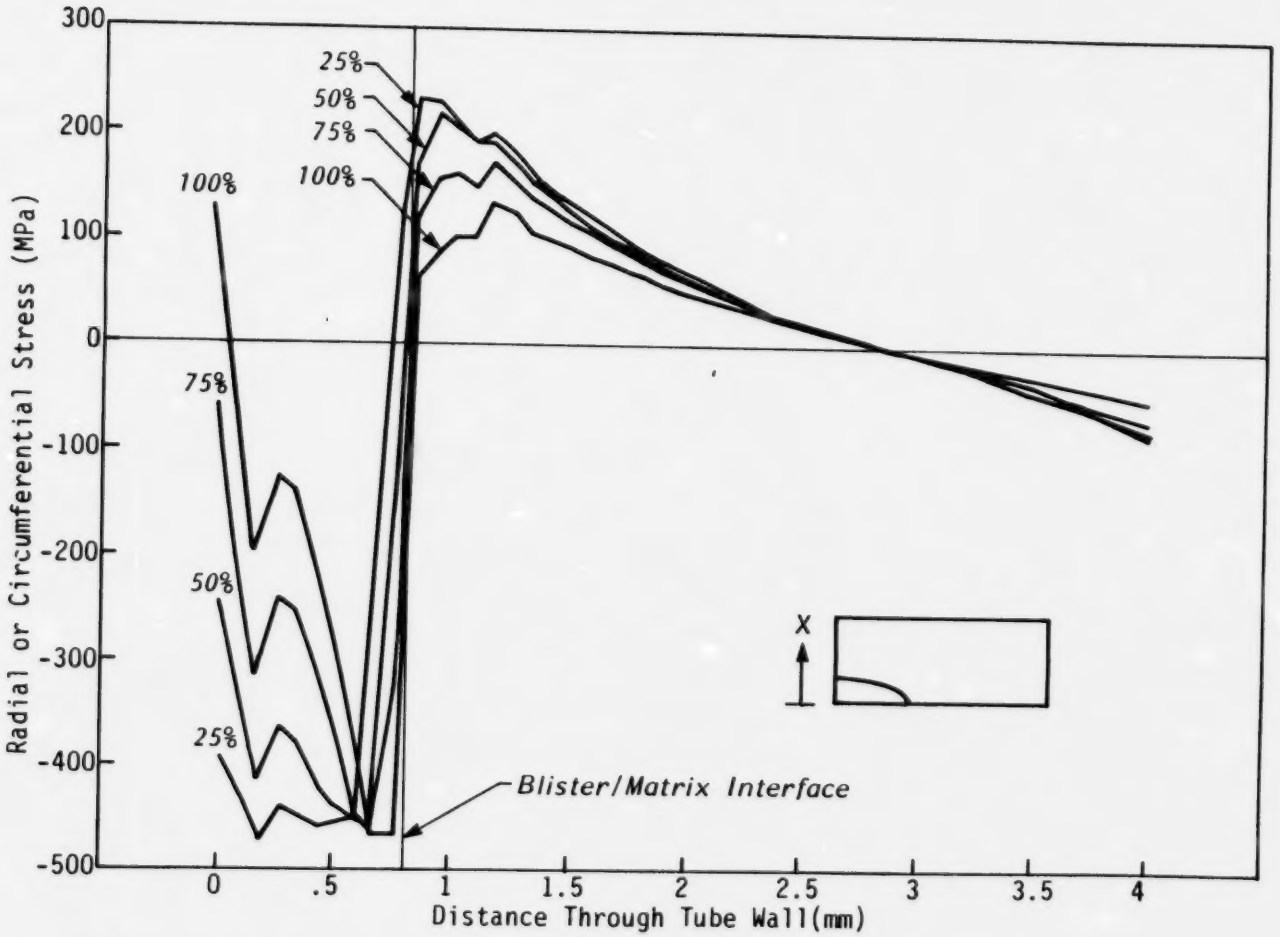


FIGURE 18

DEVELOPMENT OF THROUGH-WALL STRESSES FOR Zr-2.5Nb MESH WITH A HYDROGEN DISTRIBUTION OBTAINED FROM A NUMERICAL SIMULATION OF BLISTER GROWTH

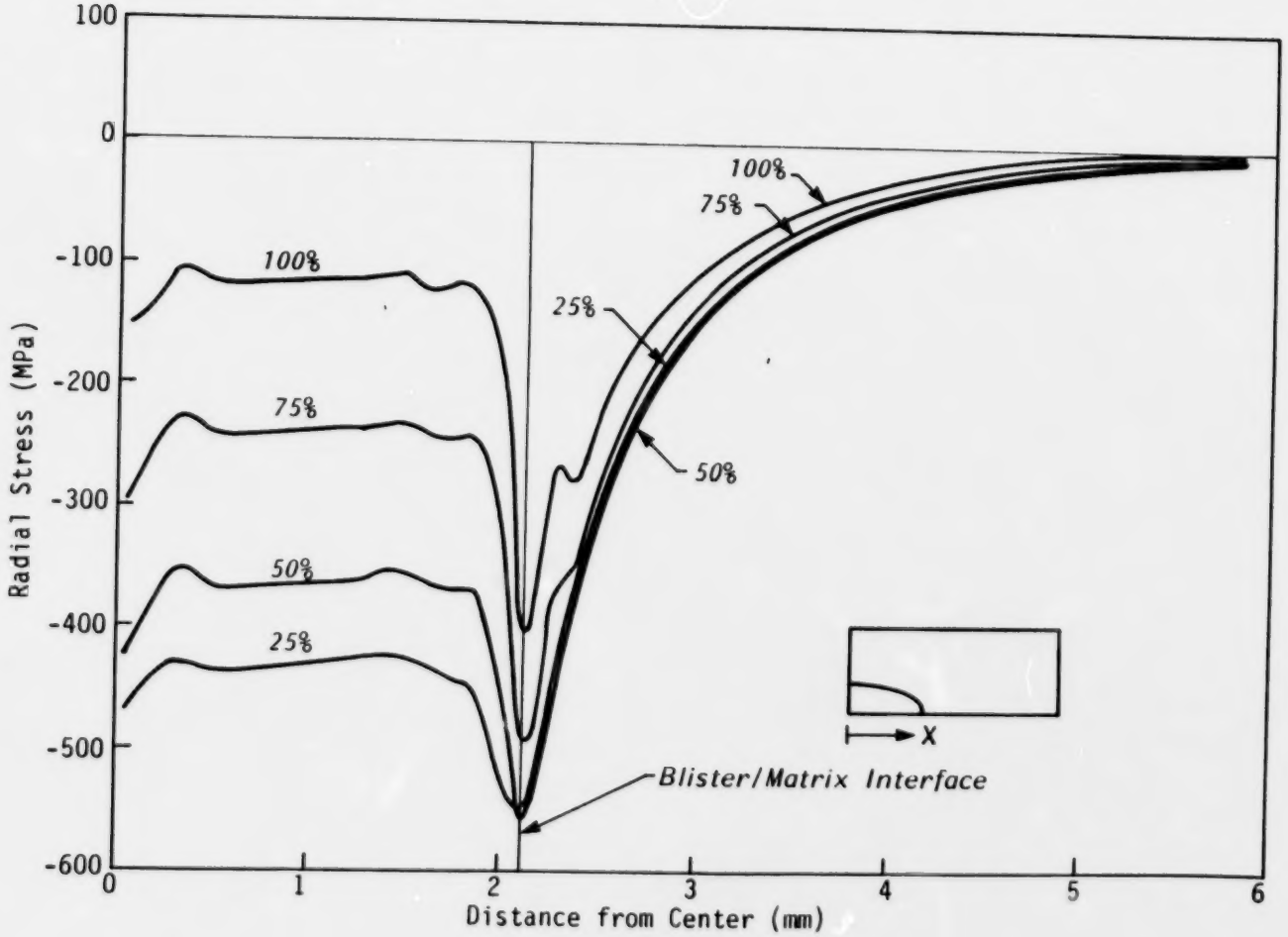


FIGURE 19

DEVELOPMENT OF OUTER SURFACE RADIAL STRESSES FOR Zr-2.5Nb MESH WITH A HYDROGEN DISTRIBUTION OBTAINED FROM A NUMERICAL SIMULATION OF BLISTER GROWTH

171083 RD

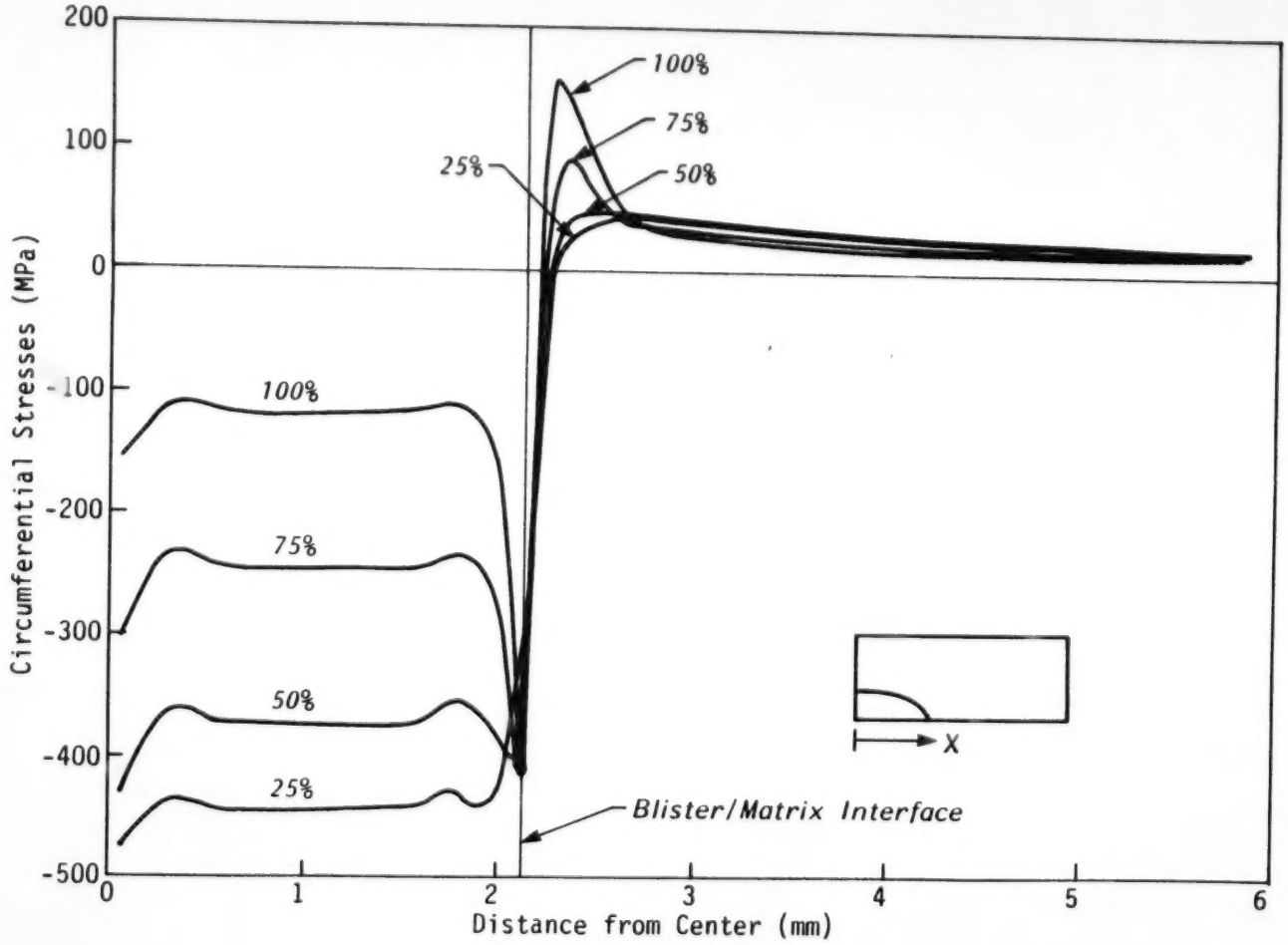


FIGURE 20

DEVELOPMENT OF OUTER SURFACE CIRCUMFERENTIAL STRESSES FOR Zr-2.5Nb MESH WITH A HYDROGEN DISTRIBUTION OBTAINED FROM A NUMERICAL SIMULATION OF BLISTER GROWTH

171082 RD

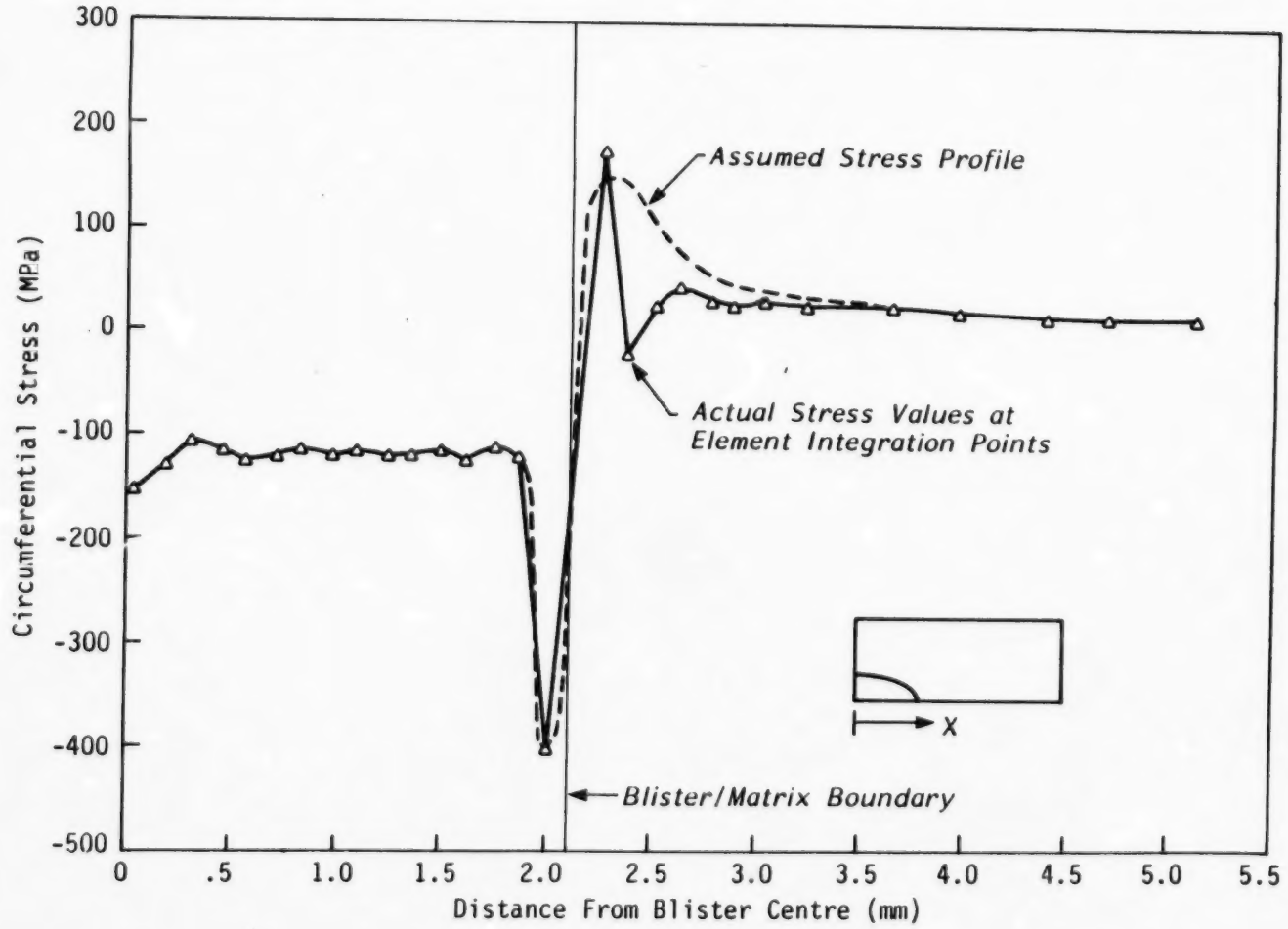


FIGURE 21

ILLUSTRATION OF NUMERICAL INSTABILITY OF INTEGRATION POINT STRESSES AT BLISTER BOUNDARY AT FULL 14.1% VOLUME EXPANSION

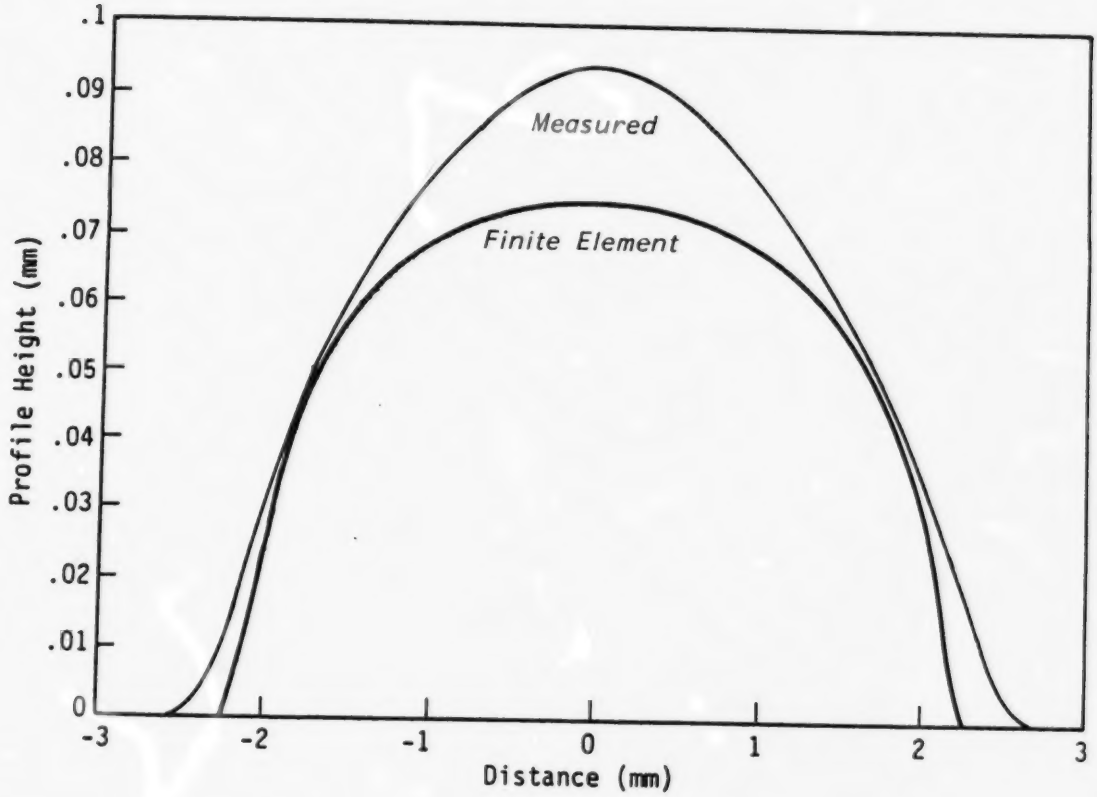


FIGURE 22

COMPARISON OF MEASURED PROFILE HEIGHT WITH PREDICTION FROM FINITE ELEMENT ANALYSIS

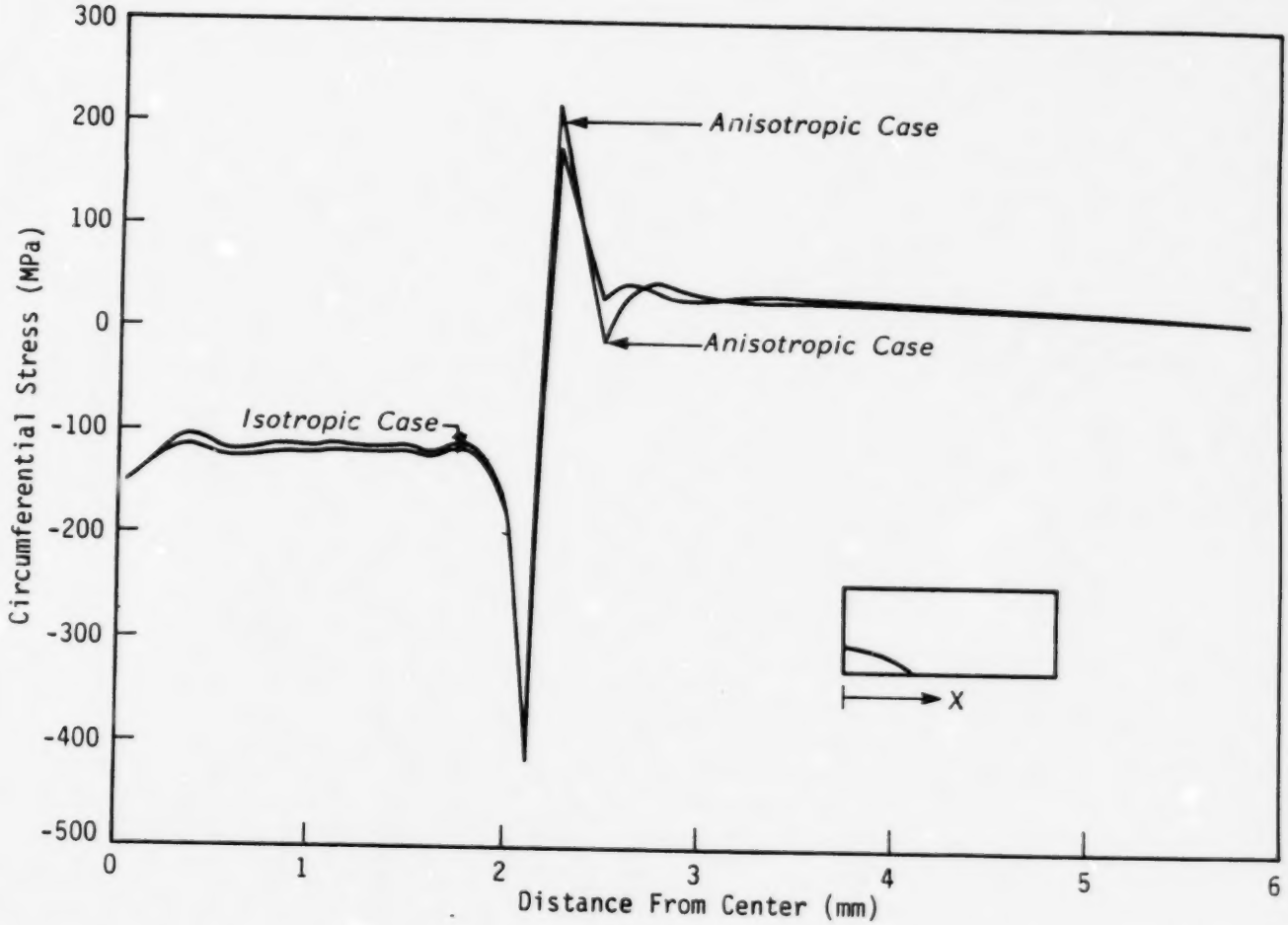


FIGURE 23

COMPARISON OF CIRCUMFERENTIAL STRESSES FOR ISOTROPIC AND ANISOTROPIC EXPANSION AT FULL 14.1% VOLUME EXPANSION (Zr-Nb MESH WITH CONCENTRATION DEPENDENT MATERIAL PROPERTIES)

APPENDIX A

Stress Contour and Deformation Plots for
Analysis with the Zircaloy-2 Mesh and
Concentration Dependent Material Properties

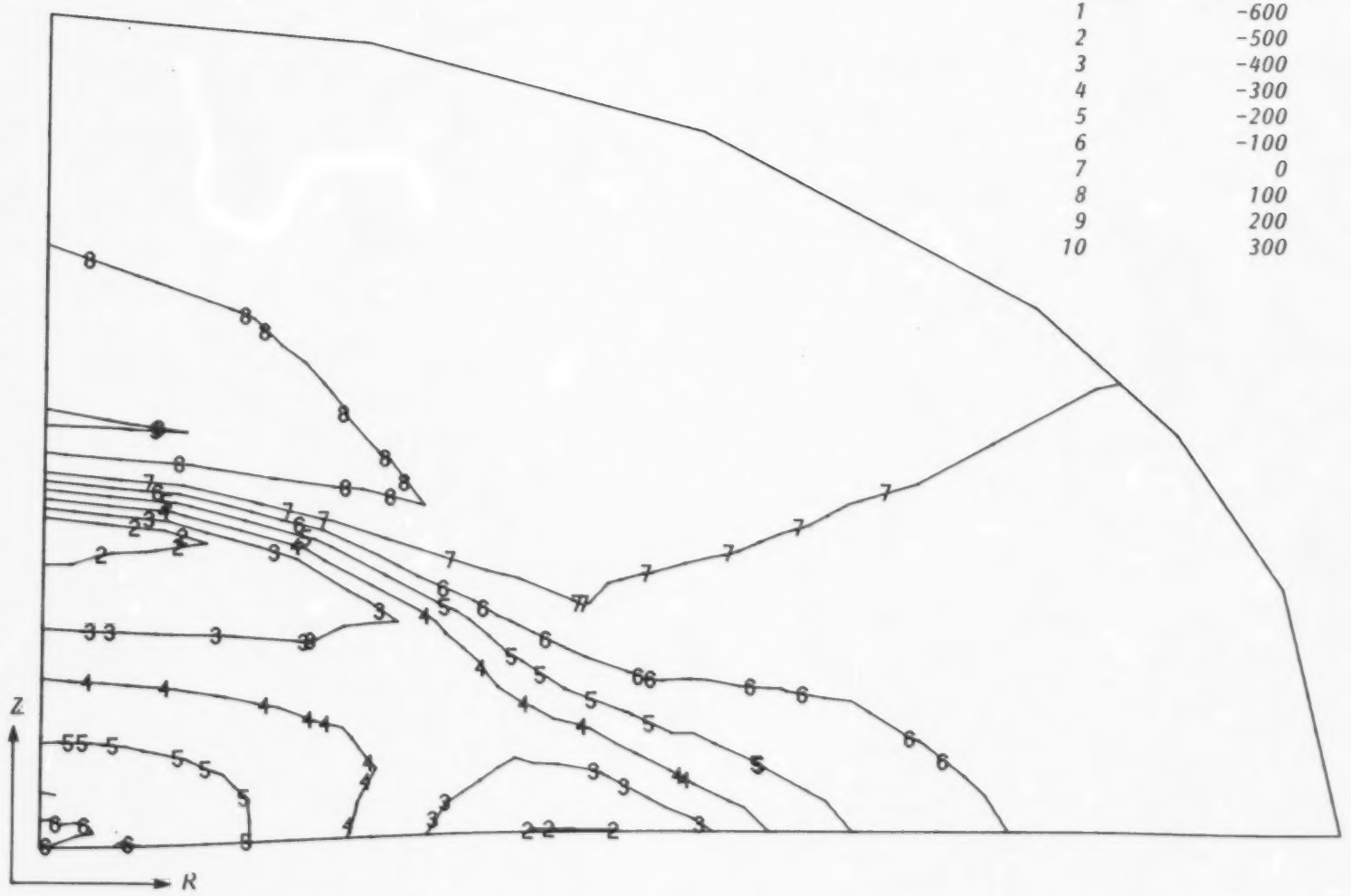
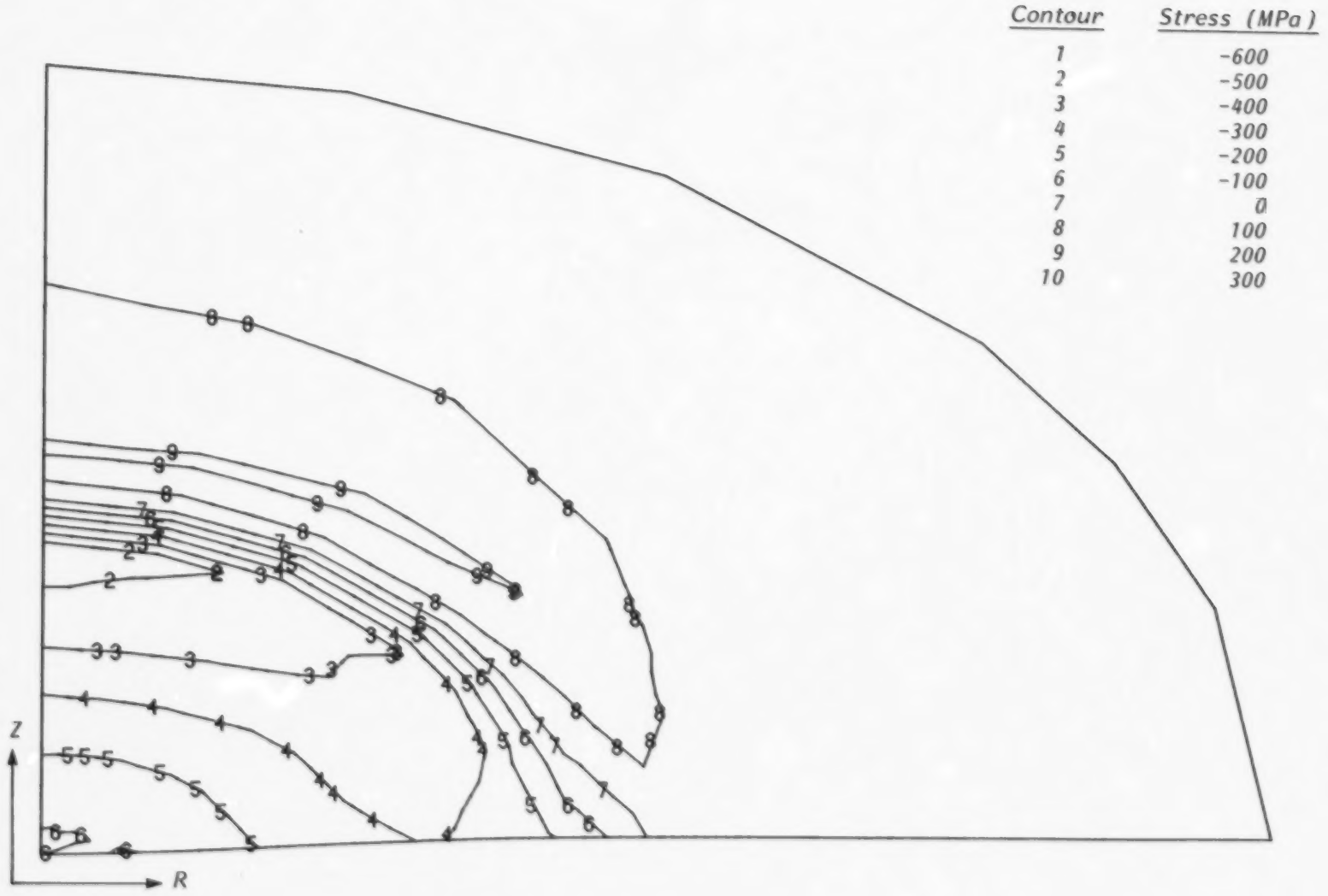


FIGURE A1

RADIAL STRESS CONTOURS AT 14.1% VOLUME EXPANSION



172203-RD

FIGURE A2

CIRCUMFERENTIAL STRESS CONTOURS AT 14.1% VOLUME EXPANSION

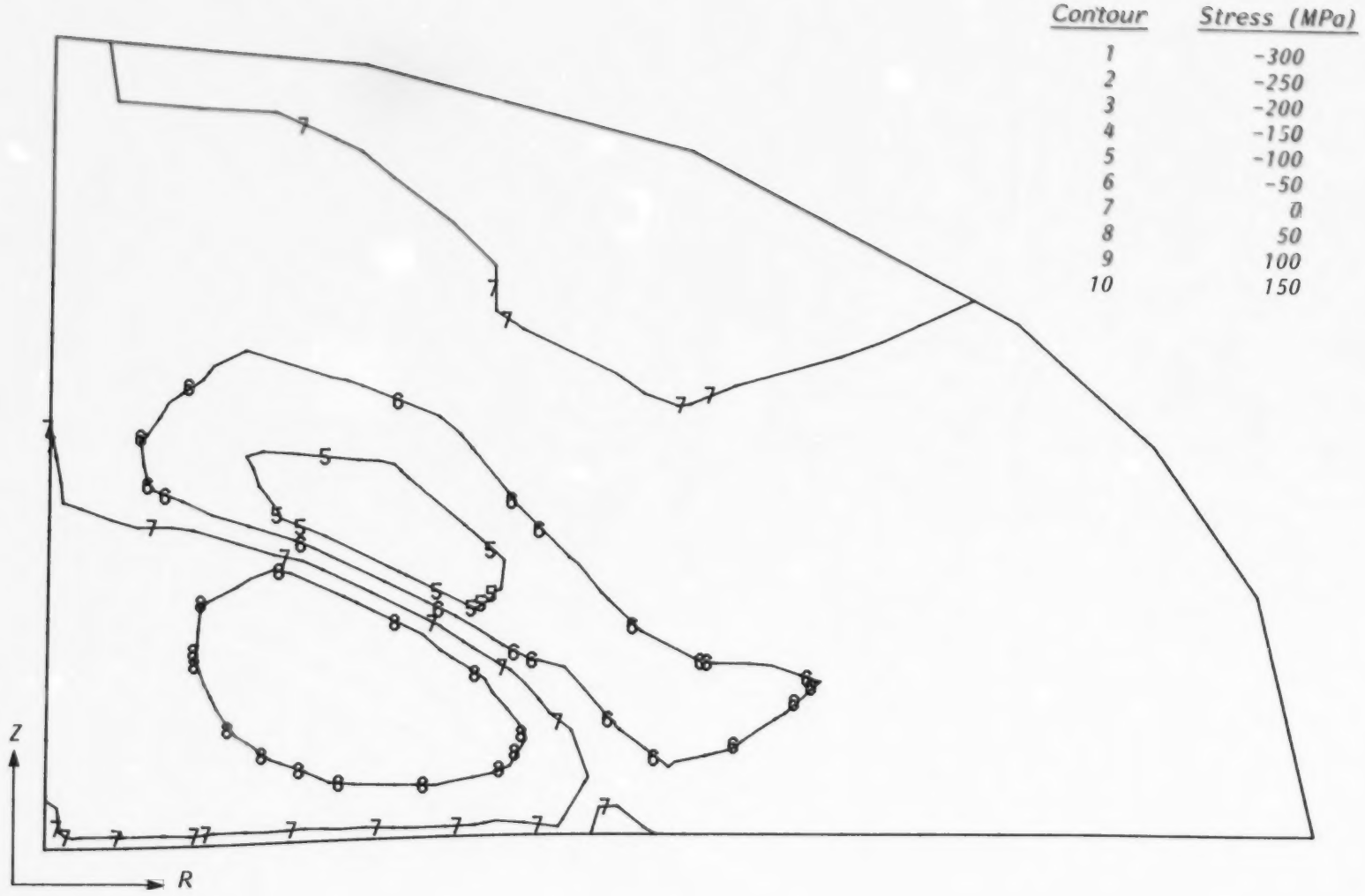


FIGURE A3

SHEAR STRESS CONTOURS AT 14.1% VOLUME EXPANSION

172204-RD

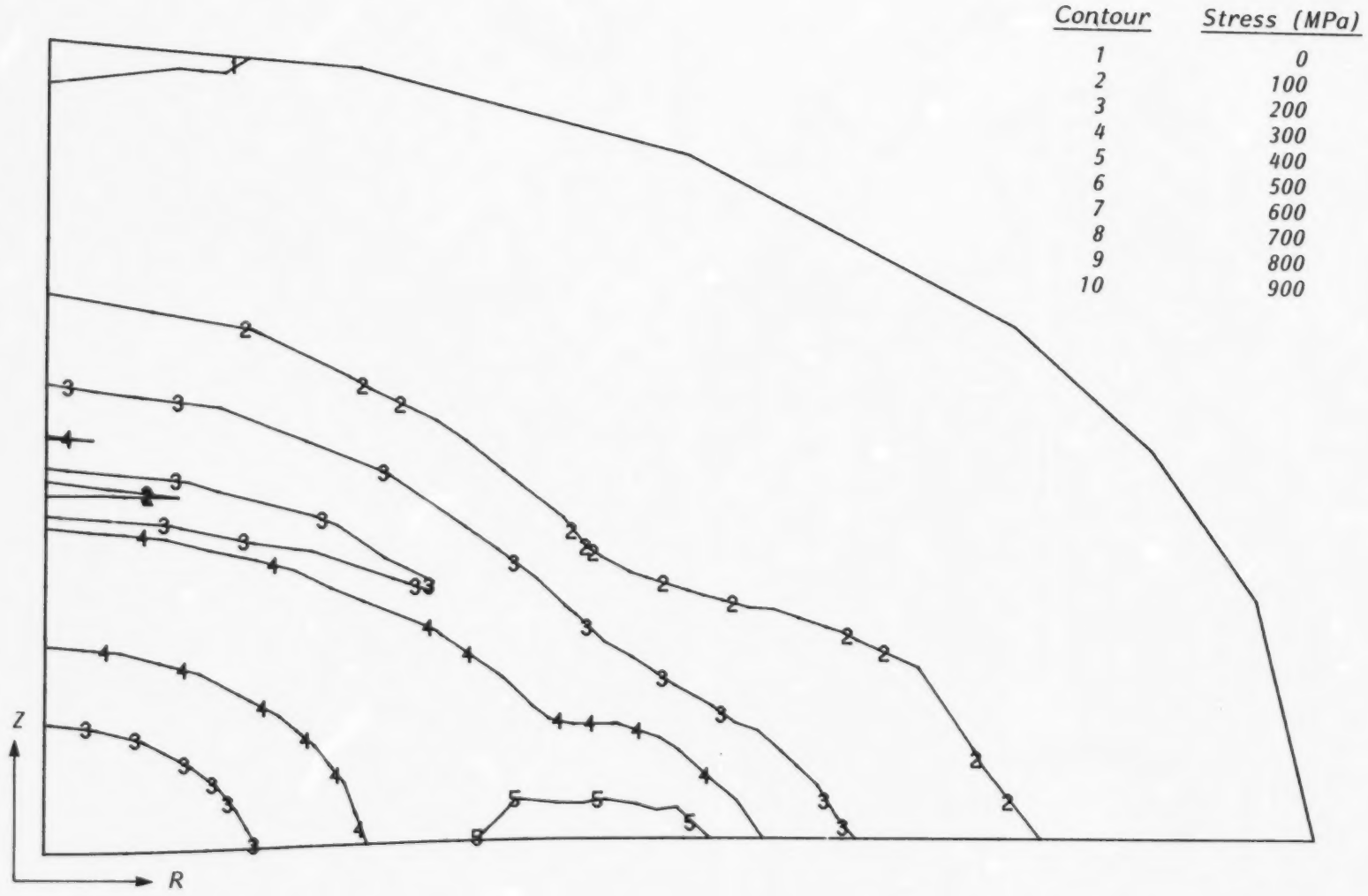
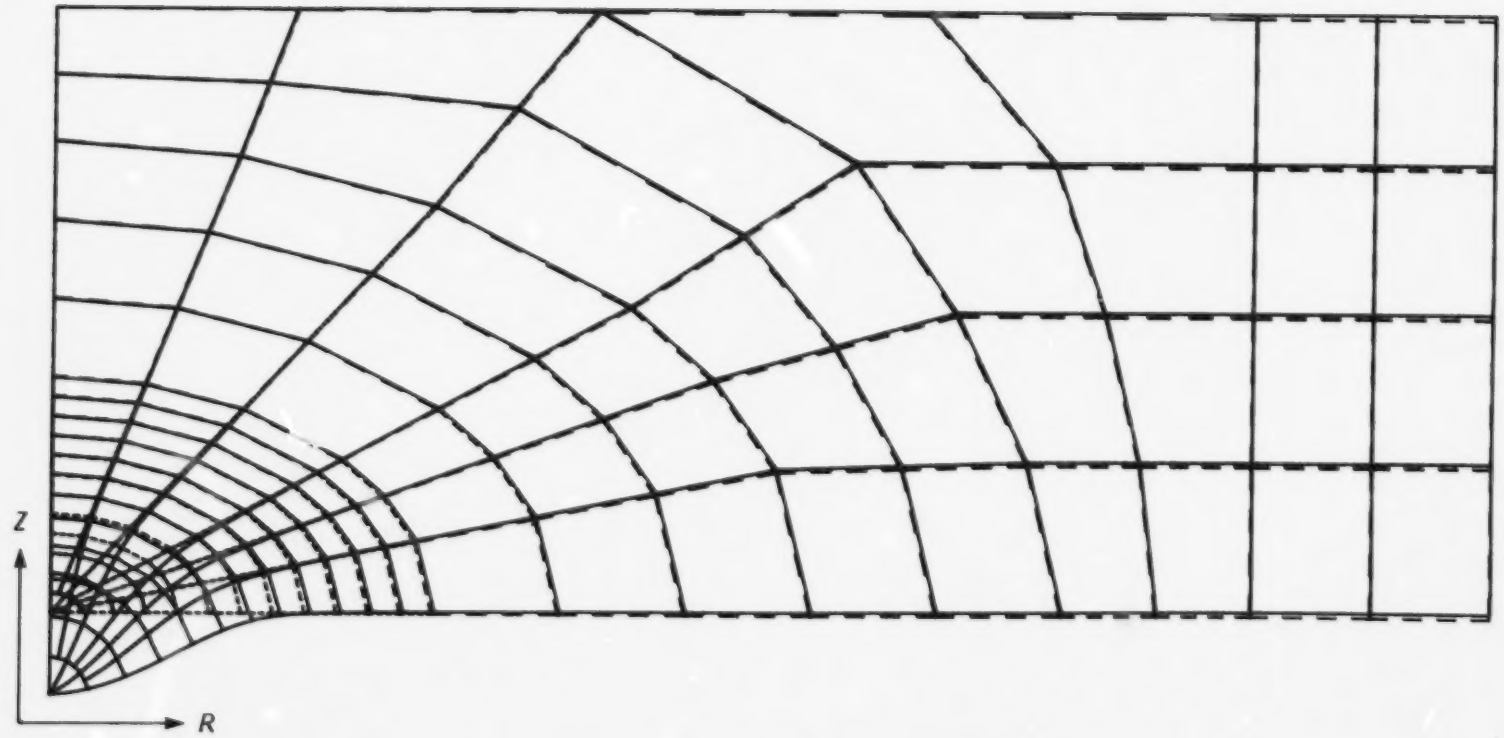


FIGURE A4

MISES EQUIVALENT STRESS CONTOURS AT 14.1% VOLUME EXPANSION

172205-RD



Solid Lines - Deformation Mesh
Broken Lines - Original Mesh
DeformationMagnification Factor = 10

FIGURE A5

DEFORMED SHAPE AT 14.1% VOLUME EXPANSION

APPENDIX B

Stress Contour and Deformation Plots for
Analyses with the Zr-2.5Nb Mesh and
Concentration Dependent Material Properties

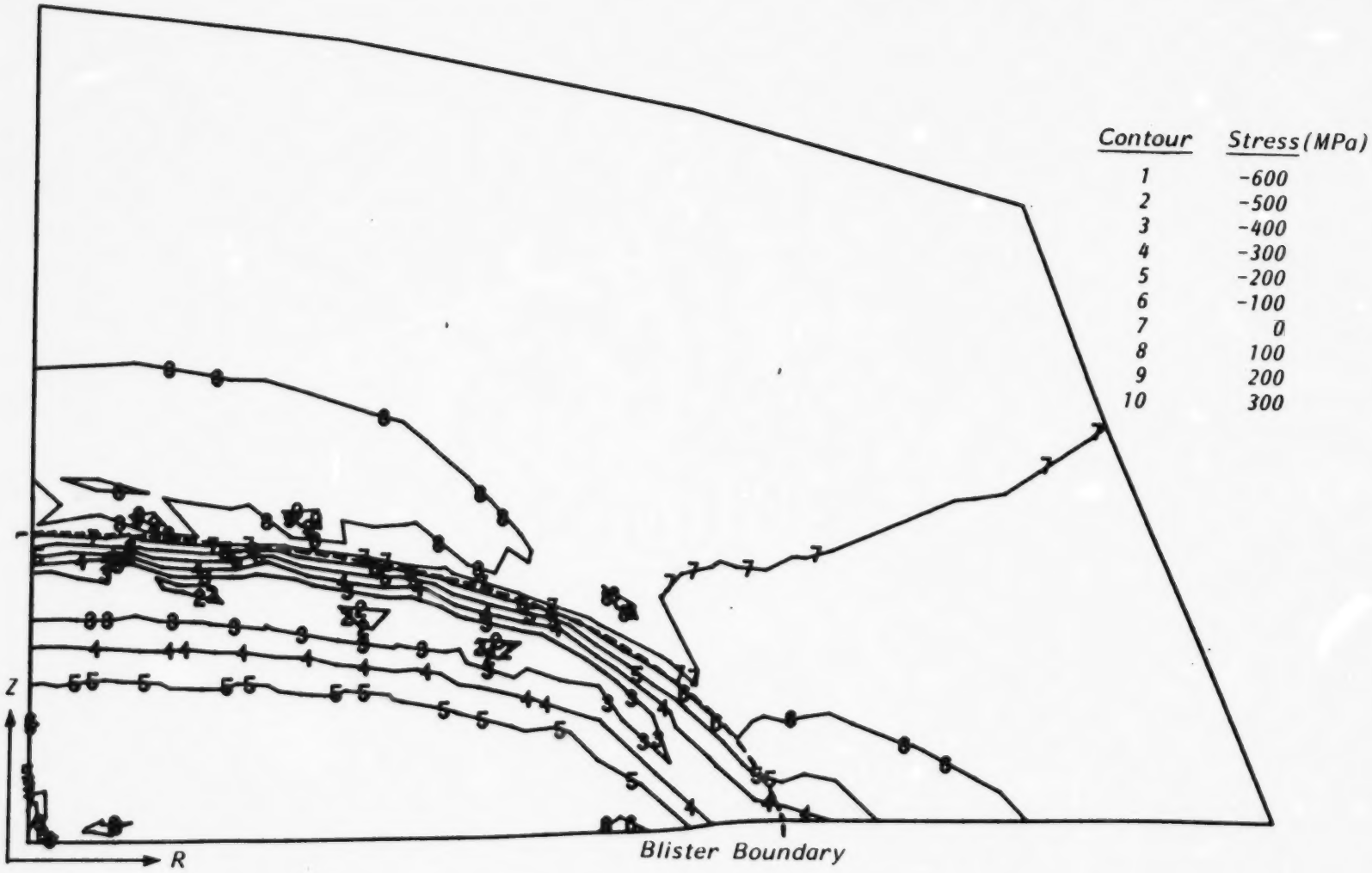


FIGURE B.1
RADIAL STRESS CONTOURS AT 14.1% VOLUME EXPANSION

171556 RD

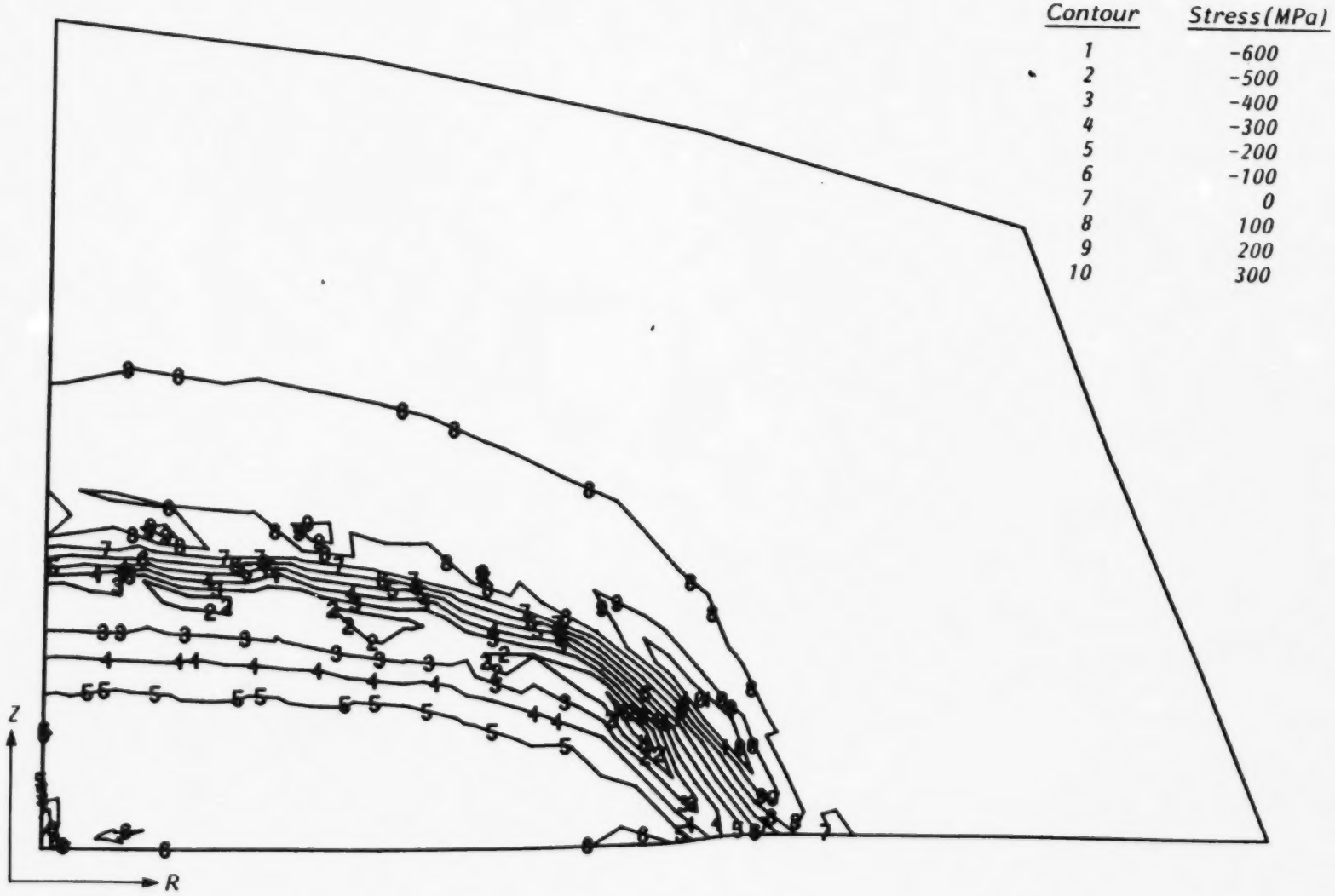


FIGURE B.2

CIRCUMFERENTIAL STRESS CONTOURS AT 14.1% VOLUME EXPANSION

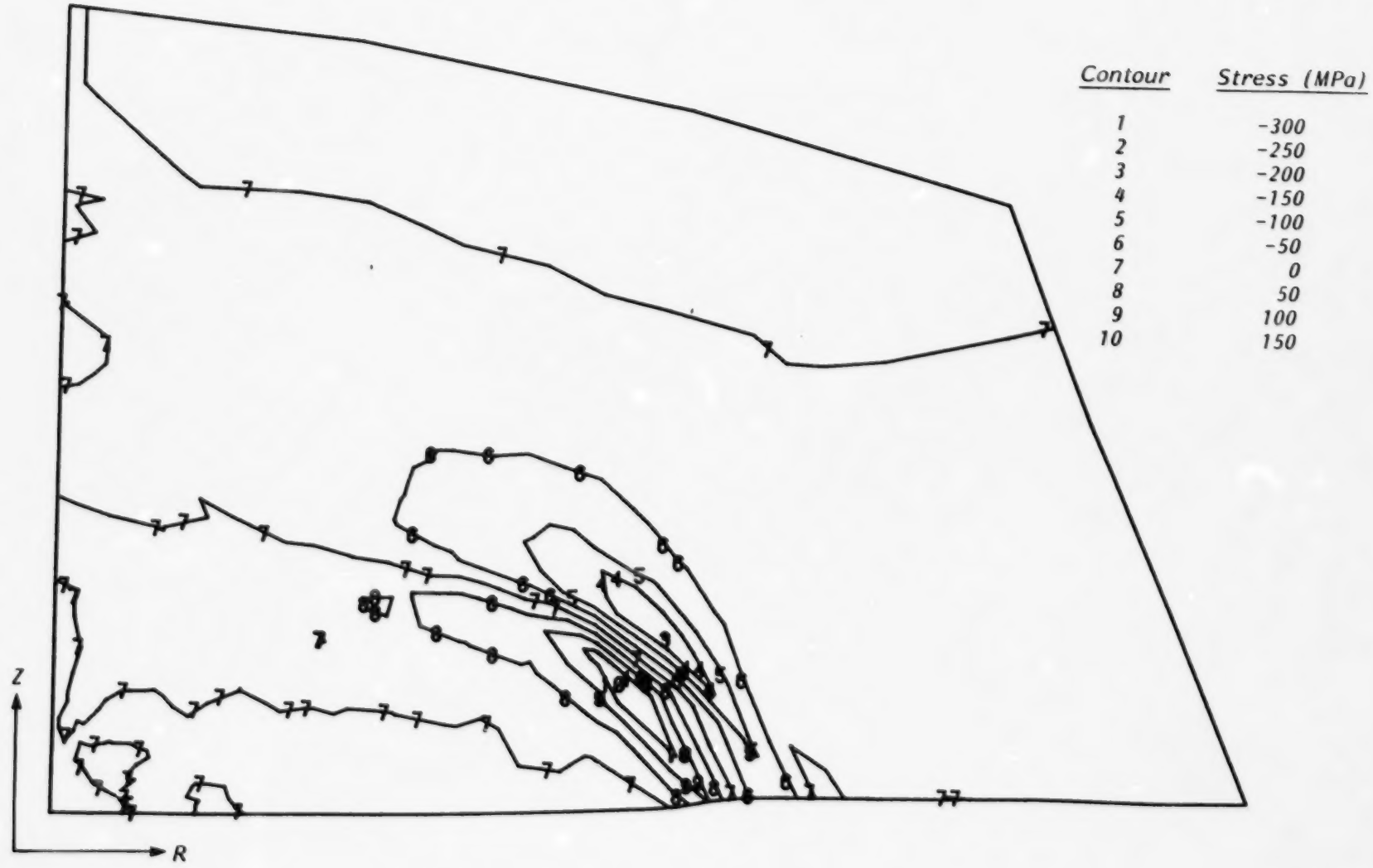


FIGURE B.3
SHEAR STRESS CONTOURS AT 14.18 VOLUME EXPANSION

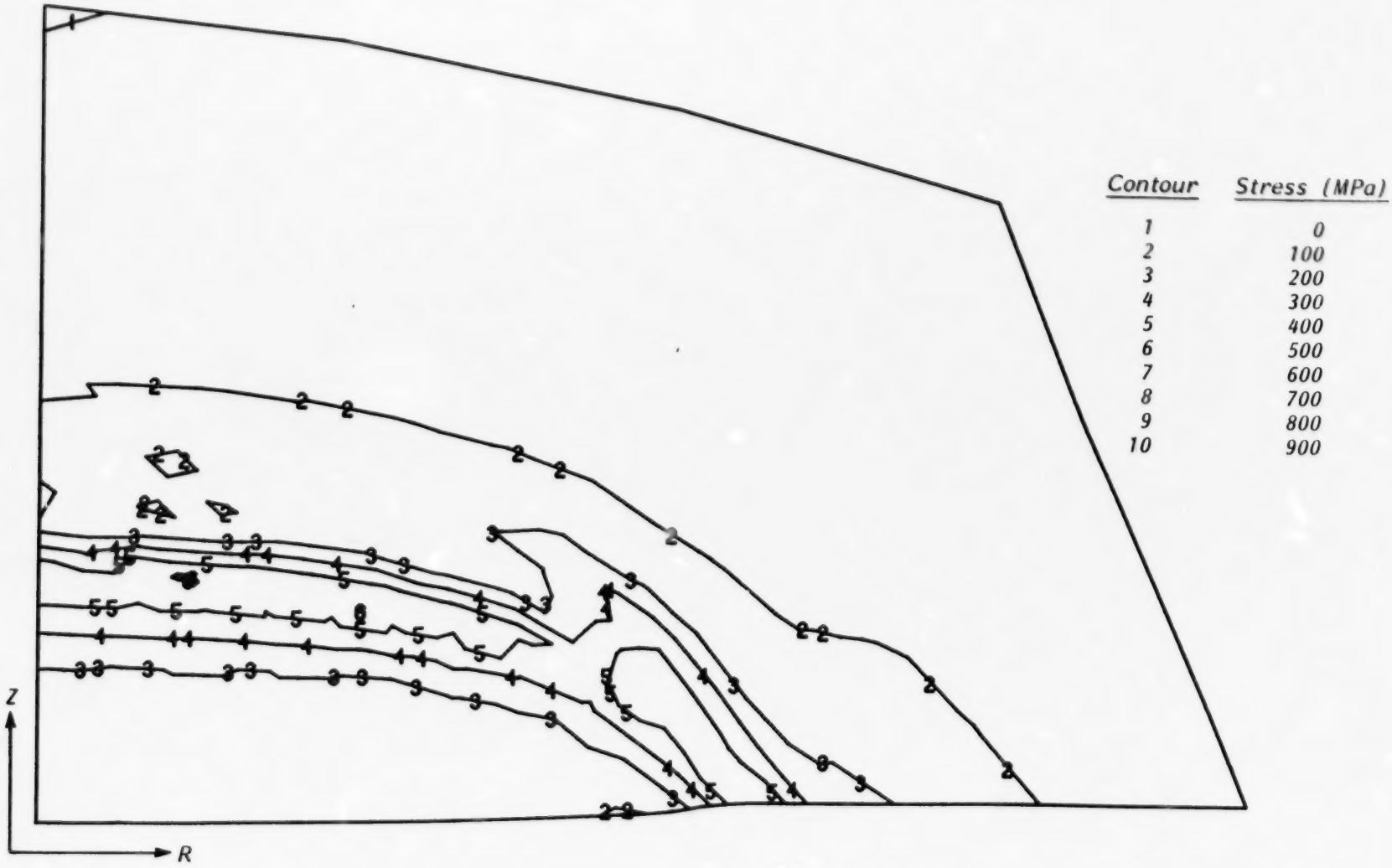


FIGURE B.4

MISES EQUIVALENT STRESS CONTOURS AT 14.1% VOLUME EXPANSION

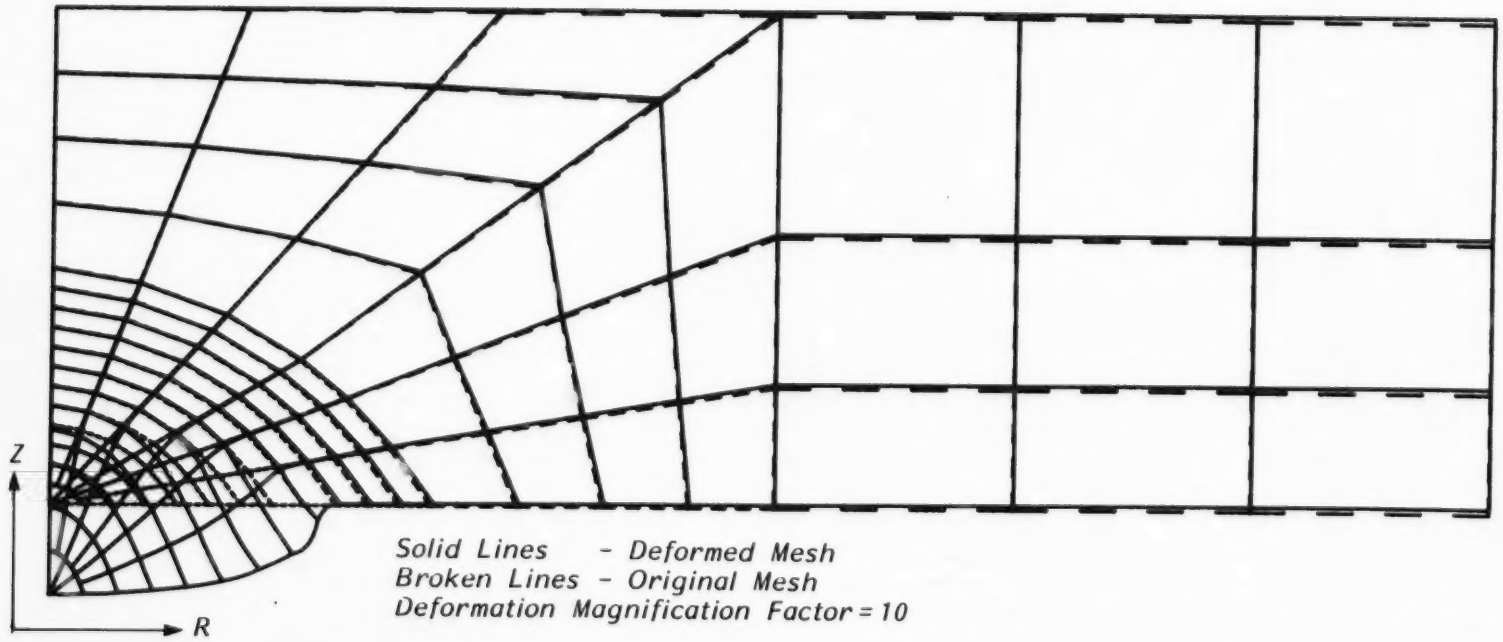


FIGURE B.5

DEFORMED SHAPE AT 14.1% VOLUME EXPANSION

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